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BOREHOLE SENSING METHODS FOR GROUND-WATER INVESTIGATIONS AT HAZARDOUS WASTE SITES

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This report covers borehole geophysical methods and addresses problems of site characterization, contaminant plume detection and monitoring of contaminant plumes.

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ABSTRACT

The complex nature of the ground-water contamination problem requires the collection of extensive amounts of data in order to understand the problem well enough to recommend and execute the appropriate remedial action. As the complexity and consequences of ground-water contamination increase, geopysical methods are becoming a cost effective approach to providing answers to hydrogeologic questions associated with ground-water contamination.

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This report covers borehole geophysical methods and addresses problems of site characterization, contaminant plume detection and monitoring of contaminant plumes.

Borehole tools and interpretation methodology have been developed primarily for the petroleum industry. The environment of the typical hazardous waste site is very different from the environment encountered in petroleum exploration, and the parameters of interest are very different for the typical hazardous waste site investigation. As a result, most borehole tools and virtually all interpretation algorithms for borehole methods are not directly applicable to hazardous waste investigations. The methods developed by the petroleum industry require modification, and in most cases, new interpretation schemes must be developed.

We have developed an interpretation strategy designed specifically to extract data of hydrogeologic interest from the subsurface. The borehole tools chosen for this strategy include natural gamma, gamma density, induction (apparent electrical conductivity of the formation), televiewer, and thermal horizontal flow meter. The data collected using these five tools are combined so that hydraulic conductivity, ground-water pore velocity, pore fluid conductivity (a measure of total dissolved solids), and anisotropy can be obtained. These data are obtained as a function of depth, thus providing valuable detailed information as input to contaminant transport models.

Laboratory experiments conducted to determine the accuracy of the thermal ground-water flow meter show that the flow meter can be used to measure ground-water velocities down to 0.5 meters per day. The results also show poor correlation between experiments conducted in the t-tube calibration and in the large sand box. As a result of this poor correlation, theoretical work was conducted to allow the ground-water flow meter to be used without

laboratory calibration and to show how the flow meter can theoretically be used to obtain aquifer hydraulic conductivity, as well as flow rate and direction.

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SECTION 1

INTRODUCTION

MONITORING GROUND-WATER QUALITY AT HAZARDOUS WASTE SITES

Monitoring of ground-water quality at hazardous waste sites is a subject of intense interest in the U.S. Environmental Protection Agency (EPA). This interest has been sparked by results of several national surveys that conclude that ground-water monitoring at both Superfund and Resource Conservation and Recovery Act (RCRA) waste disposal sites falls short of acceptability. Problems identified during a EPA study of 22 RCRA sites (R. Murphy, EPA-Washington DC, personal communication, 1985) include:

- Wells at about 50 percent of the sites are screened incorrectly. Consequently, contaminant plumes that intersect the wells are not intercepted by the screens.
- Wells at 30 percent of the sites are incorrectly placed, so that the contaminant plume does not intersect the well at any depth.
- For 10 percent of the sites, placement of monitoring wells occurred before the direction of ground-water flow had been determined.

A more complete understanding of the site hydrogeologic setting would minimize such problems. Subsurface information is required to determine hazardous waste site hydrogeologic conditions, locate contaminant plumes, and monitor sites for leaks from disposal facilities. Borehole geophysics, in conjunction with surface geophysics and other geologic and hydrologic techniques, can aid in determining site hydrogeologic parameters, particularly in the third dimension. Borehole geophysics can contribute significantly to our understanding of: lithology, porosity, and structure; zones of saturation; physical and chemical characteristics of fluids; and ground-water flow speed and direction.

THE PROBLEM OF CONTAMINANT TRANSPORT AND HAZARDOUS WASTE

Until the early 1970's, the science of hydrogeology was primarily concerned with water supply, which is often referred to as the "ground-water quantity problem". This problem is solved by determining the piezometric head or water table elevation distribution in time and space in response to stresses on the aquifer system. Aquifer tests to determine hydraulic parameters have been in routine use for more than 20 years. Numerical models that provide predictive models for changes in head distribution are also used routinely.

Concern over the contamination of ground-water supplies has changed the primary emphasis of hydrogeology from problems of ground-water quality problem to problems of ground-water quality. The ground-water quality problem concerns the transport of solutes (contaminants) in ground water. To determine rates of contaminant transport, ground-water velocity must be known. However, velocity data are normally obtained by indirect methods. This is true for measurement of velocity in the field and calculation of velocity in models. Variations in ground-water velocity owing to the heterogeneous nature of the aquifer cause dispersion of the contaminant. Thus the contaminant will have a velocity different from the average velocity of the ground water. The difficulty of obtaining accurate velocity measurements, as well as other difficulties, makes solving the ground-water quality problem much more difficult than solving the quantity problem. In addition, contaminated ground water at hazardous waste sites is likely to contain numerous contaminants, making the problem considerably more complex.

Understanding the complex nature of the ground-water contamination problem well enough to recommend and execute an appropriate remedial action requires that extensive amounts of data be collected. It is nearly impossible to collect adequate amounts of data using traditional hydrogeologic methods, consequently, new technology is needed.

Geophysical methods have been widely used in oil and mineral exploration since the 1920's. However due to their cost and the relative simplicity of most previous ground-water problems, geophysical methods have not commonly been used. As the complexity and consequences of ground-water contamination increase, geophysics is becoming a more cost effective approach to answering the hydrologic questions associated with ground-water contamination.

A possible goal of a contaminant study is to recommend remedial action that will either clean up the contaminated ground water or prevent it from entering the biosphere. However, before remedial action can be taken, it is necessary to understand the extent of the problem and the hydrogeologic conditions present at the contaminated site. There are many ways to approach this problem, but from the standpoint of RCRA, the problem can be divided into three categories: site characterization; contaminant plume detection; and monitoring of contaminant plumes.

SITE CHARACTERIZATION

The characterization of a contaminated (or potentially contaminated) site consists primarily of determining local hydrogeology and contaminant plume distribution. Most sites are small compared to the regional hydrogeologic system, and the regional gradient can be superimposed on the local system to obtain a general flow direction. Structural geologic information can provide a picture of the geometry of the contaminated aquifer. Aquifer tests provide information on the horizontal hydraulic conductivity and storativity of the aquifer. The storativity is unnecessary from the standpoint of contaminant transport, because the fluid mass conservation equation is usually solved as a steady-state equation. The hydraulic conductivity data obtained from aquifer tests are of limited value because of the spatial variability of aquifer properties, which greatly affect the transport of contaminants. Of particular importance is the hydraulic conductivity variation in the vertical direction. Aquifer tests are of limited use for vertical variations because they produce hydraulic conductivity values that are integrated over the vertical domain. Testing of individual strata can be done if the strata

are horizontally extensive, but this is most often not the case in shallow, unconsolidated sediments. In an anisotropic aquifer, the solute can be transported in a direction different from the gradient, thus anisotropy is a very important parameter for contaminant studies. Measurement of the hydraulic conductivity tensor requires a minimum of three observation wells. The aquifer must be homogeneous over the area of these observation wells, which is usually a poor assumption for shallow, unconsolidated sediments. There is a clear need to develop methods that will be useful in determining spatial variability and anisotropy for hydraulic conductivity.

CONTAMINANT PLUME DETECTION

Mapping the location and distribution of contaminants in ground water ("contaminant plume detection") is a difficult problem because of the inaccessibility to the affected environment. Direct sampling methods are limited to monitoring wells. To adequately determine contaminant concentration and plume migration, a large number of costly monitoring wells must be drilled.

MONITORING CONTAMINANT PLUMES

Ground-water monitoring is required under RCRA regulations at hazardous waste facilities. A successful monitoring network will detect a leak from a permitted hazardous waste facility or detect changes in ground-water quality in an aquifer near a hazardous waste site. A well-designed monitoring network should conform to a number of important criteria. Zones of high permeability should be located and specifically monitored, because they are most likely to contain the first arrival of a contaminant. The directional component of the ground-water velocity will be the primary consideration in locating up- and down-gradient monitoring wells. Often, monitoring of contaminant plumes is thought of in terms of looking for certain parameters. In this sense, a parameter is a property or characteristic of the ground water or the aquifer itself which has been selected for monitoring because it is indicative of a condition or state of contamination. The chemical, physical, and electrical properties of the ground water are important in determining what parameters should be monitored.

PURPOSE AND SCOPE

Geophysical methods applicable to hazardous waste site investigations can be broken into two categories: surface and subsurface methods. Surface methods offer the advantage of relatively little capital investment at the site (no borehole is required), and rapid collection of data over a horizontal area. However, the interpretation is often ambiguous and limited in vertical resolution. Subsurface methods require a borehole and can only be used to investigate an area immediately around the borehole. However, they provide excellent information on vertical changes in measured parameters. Also, a suite of complementary logs can potentially provide unambiguous interpretation of hydrogeologic data.

The two approaches complement each other very well. The subsurface methods provide the necessary vertical detail for a small area, and the surface methods are used to extend this detail horizontally between boreholes.

In this report, the problems of site characterization, contaminant plume detection and monitoring of contaminant plumes are addressed using borehole geophysics. The overall goals

of this project are to:

1. Determine which traditional and nontraditional borehole methods are best for addressing the problems of site characterization and plume detection and monitoring.
2. Develop a borehole logging interpretation strategy that can be used at hazardous waste sites and that is designed specifically to address the determination of hydrogeologic parameters.
3. Develop procedures for using the borehole thermal flow meter to obtain ground-water velocity and hydraulic conductivity data.

Originally, this report was to include procedures for all borehole tools recommended in the borehole logging interpretation strategy. Because of problems beyond the control of EPA and the Desert Research Institute, University of Nevada System (DRI), the only logging tool available to fully test was the borehole thermal flow meter. The procedures for using the rest of the recommended suite of borehole logs with the interpretation strategy will be covered in future reports, after the logging tools have become available and the strategy has been proven to work, or has been refined as necessary.

APPROACH

Section 2 provides a description of the traditional and nontraditional borehole logging methods, including principles of operation, discussion of the properties that the tools measure, and the parameters that the log analyst normally obtains from interpreting the logs. Emphasis is placed on the objectives of traditional borehole logging. More information is provided for the tools that will be singled out as useful for the interpretation strategy outlined in Section 4.

Section 3 discusses the limitations of traditional borehole logging techniques. The discussion provides the reader with the reasons why it is necessary to develop an entirely new and different borehole logging strategy for hydrogeologic applications.

Section 4 outlines the interpretation strategy. The strategy that is presented is only one alternative. Actual use of the strategy has not yet occurred, due to lack of equipment. The strategy will be refined and improved based on the experiences of actual use.

Section 5 presents the results of a detailed set of calibration procedures that were conducted with the borehole thermal flow meter. Recommendations for its use are presented. Procedures for the use of the flow meter to determine aquifer hydraulic conductivity are developed. The hydraulic conductivity procedures have not been tested, and their verification will be the subject of a future report.

Section 6 presents the project summary, conclusions and recommendations.

SECTION 2

BOREHOLE GEOPHYSICAL METHODS

TRADITIONAL USE AND PURPOSE OF BOREHOLE GEOPHYSICAL METHODS

A widely accepted definition of borehole geophysics can be found in Keys and MacCary (1971):

> Geophysical well logging, also called borehole geophysics, includes all techniques of lowering sensing devices in a borehole and recording some physical parameter that may be interpreted in terms of the characteristics of the rocks, the fluids contained in the rocks, and the construction of the well.

This definition reflects the historical development and use of borehole geophysical methods.

The first known use of a borehole method was to measure the borehole fluid temperature as a function of depth (Hallock, 1897). The first major borehole method to be developed was in the area of borehole electrical resistivity by Schlumberger (1929). The work was done in an oil field in France, and most borehole methods were subsequently developed in response to needs of the oil industry.

The use of borehole geophysics by the water well (or ground-water supply) industry has been limited by a number of factors. The cost/benefit ratio of using borehole methods in pure ground-water supply investigations has traditionally been unfavorable compared to using borehole logging in the field of petroleum exploration. Most water wells tend to be shallow relative to oil wells, and borehole methods have been developed for deep well application. In the oil industry, borehole methods have been used to help locate new wells to maximize product recovery. The criteria for locating water wells are more often related to cultural necessity, such as locating the well near population centers, and locating shallow water sources to minimize pumping costs.

In recent years, considerable attention has been focused on the problems of ground-water contamination, especially at hazardous waste sites. The amount of money being spent on the clean up of hazardous waste sites is very large, especially compared to traditional ground-water supply investigations. As a result, borehole geophysical methods are no longer considered to be relatively costly. This has created a need to develop borehole tools and interpretation strategies that can be used in ground-water contamination studies.

Some of the basic reasons for doing geophysical well logging include:

1. To allow visual interpretation and comparison at the well site.
2. Immediate decisions can be made regarding screening intervals.
3. Well logging is superior to and less expensive than continuous coring (an alternative way to obtain subsurface information).
4. Well logging provides information on lithologic boundaries.

A well log itself is of limited use without applying some sort of interpretation to the raw data. Nearly all log interpretation in the petroleum industry is designed for open hole wells, the logging done prior to installation of casing.

The objectives of open hole log interpretation include:

1. Remove drilling, mud and borehole effects from logging data.
2. Determine rock properties, such as porosity, lithologic traps, and absolute, relative and effective permeability.
3. Determine formation fluid properties such as oil and gas specific gravity, hydrostatic pressure, fluid saturation distribution and temperature.
4. Obtain information on the formation factor, which leads to determination of porosity, permeability and pore fluid conductivity.

EFFECTS OF THE BOREHOLE ENVIRONMENT

Introduction

The methods of drilling and completion of a borehole will affect the types of geophysical logs that can be run and the interpretations of the data from them. If the hole is in unconsolidated sediments, the typical case in the vicinity of many hazardous waste sites, the matrix is friable and collapses easily. One way of coping with this condition is by adding various materials to the drilling fluid; usually the weight of the column of drilling fluid is greater than the pressure of fluids in the matrix rock. This achieves mechanical stability of the hole by applying backpressure to the formation; that is, stability is achieved at the cost of causing the drilling fluid to enter the pores of the formation. This immediately changes the physical properties of the formation near the borehole, which is highly undesirable if the purpose of making the hole is to ascertain the physical properties of the formation and/or its fluid contents.

The type of material used to case a hole is important. Typical materials include steel, aluminum, PVC or other plastics, and Teflon. Whether the borehole is air or liquid filled will also affect the geophysical methods available for use in them.

Effects of drilling fluids

After the hole is drilled, the logging tools are lowered into the drill hole to make measurements that are hopefully representative of the formation. Such observations must be adjusted for the changes which have been created in the vicinity of the hole by the drilling operation. As an illustration, consider Figure 2.1. The electrical resistivity (a very significant indicator of the type and amount of liquids in the pore space) changes considerably as a function of radial distance from the axis of the drill hole. The drilling fluid has entered into the formation since it is, for safety reasons, at a slightly higher pressure than the ambient formation pressure. Some of the material in suspension has been filtered out at the surface of the sidewall to form a mudcake. The rest of the drilling fluid, which is called the filtrate,

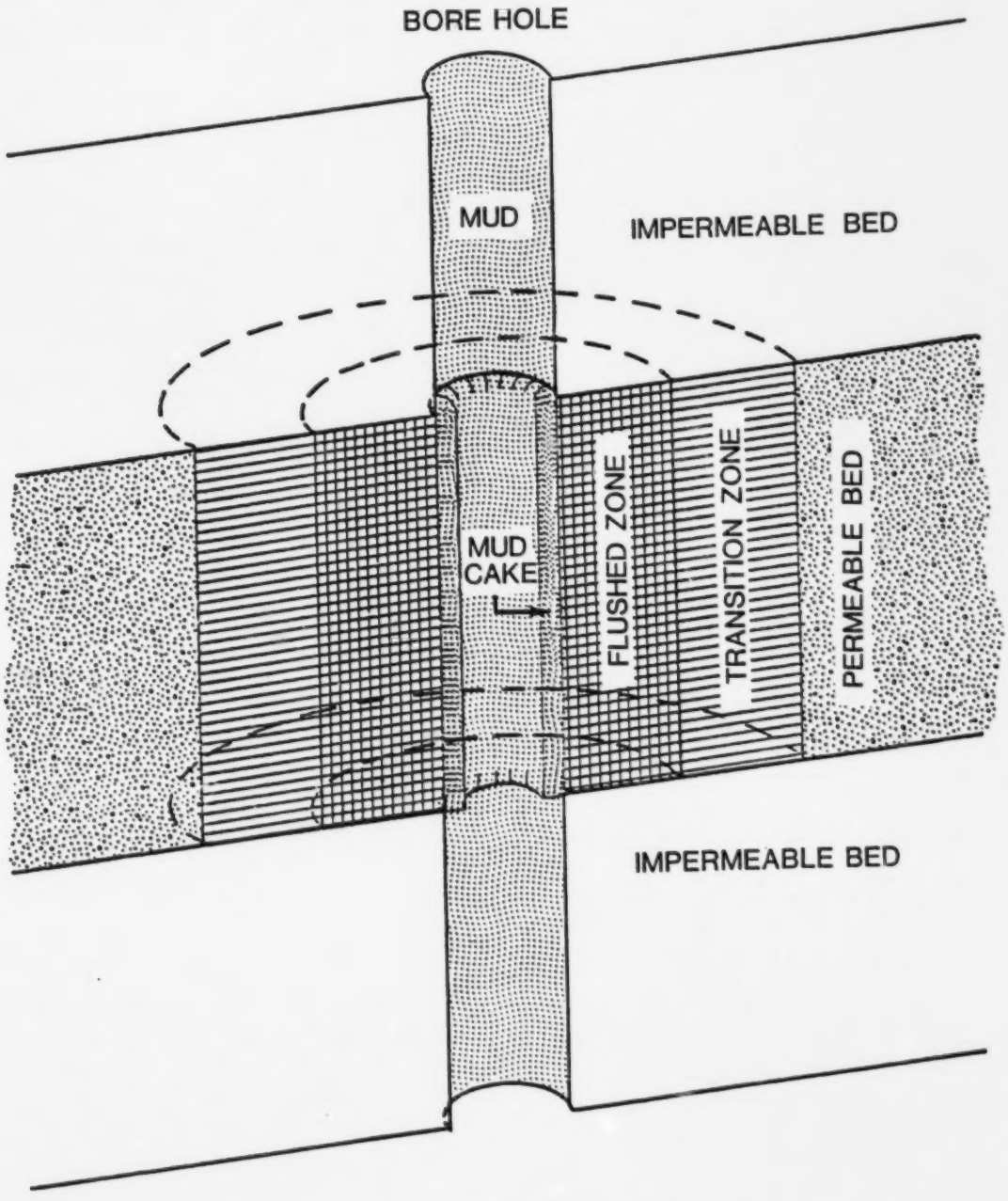


FIGURE 2.1. Change of Pore Fluid in Vicinity of Borehole.

continues penetrating into the formation; the extent of the formation so penetrated is called the invaded zone. The filtrate varies throughout the invaded zone to the percentage of pore space that is occupied. If the filtrate occupies all of the pore space, then that portion of the invaded zone is termed the flushed zone; the remaining portion of the invaded zone is called the transition zone. Note that the electrical resistivity of the mud is intermediate in value between the resistivity of the mudcake and the resistivity of the filtrate.

The size of the flushed zone or the invaded zone will change over time. Therefore, it is important to correct the geophysical and geochemical observations for the conditions which existed at the time of data collection. This evaluation is especially important in the monitoring phase of hazardous waste site operations because temporal changes in borehole logs might be mistakenly attributed to contamination instead of borehole environment changes.

Casing type

The usual material used for casing a hole is steel due to its strength; however, for shallow holes, those less than a few hundred meters, other tubing such as PVC, Teflon, or other plastics can be used. This is especially appropriate to monitoring operations in which the hole is to be used repeatedly over time. Many of the logging techniques cannot be applied in a hole cased with metal.

Summary

Table 2.1 shows the various geophysical methods which are appropriate to the wet or dry and cased or uncased hole. This is not meant to be an exhaustive presentation, simply illustrative of the constraints of the hole conditions on the geophysical information that can be obtained from the hole. Note that the radiation techniques are the most versatile, being meaningful in an open hole or a cased hole. When used in a cased hole, interpretation is easier and better if the same log has been run in the same hole before it was cased. The induction techniques can be used in place of contact resistivity techniques for the typical plastic-cased holes found in hazardous waste site investigations. Geochemical methods are sometimes used in liquid-filled holes to sample the ambient liquids. If information on depth dependence is sought, then much more complicated instrumentation is usually required.

TRADITIONAL BOREHOLE LOGGING METHODS

Descriptions of the various borehole techniques and equipment are given below. The descriptions are rather short because the equipment and interpretation techniques are open hole, and their application in hazardous waste investigations is limited. Enough detail is provided to set the stage for the discussion of limitations in Section 3. Numerous references are available that provide detailed instructions on the use of borehole logging tools and the interpretation of open hole logging data. See for example Schlumberger (1972), Asquith (1982), Hilchie (1982) Dresser Atlas (1982) and Keys and MacCary (1971). In Section 4, an interpretation scheme is developed specifically for application to ground-water investigations at hazardous waste sites, and the borehole methods useful for this application are discussed individually.

Borehole methods fall into five major categories: acoustical, electro-magnetic, nuclear, flow and dimension and thermal. Major applications of these techniques include: lithologic correlation, lithology, rock density, fractures, porosity, permeability, flow, water level, water

TABLE 2.1

BOREHOLE SENSING TECHNIQUES APPLICABLE TO VARIOUS BOREHOLE ENVIRONMENTS

Logging Techniques																		
	Single Well						Cross Borehole						In Situ					
	PVC * Cased		Steel Cased		Uncased		PVC * Cased		Steel Cased		Uncased		PVC * Cased		Steel Cased		Uncased	
	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY
ACOUSTIC					●						●							
ELECTRIC	●				●	●					●						●	●
INDUCTION	●	●			●	●	●	●			●	●						
NUCLEAR	●	●	●	●	●	●												
FLOW	●		●		●		●		●		●		●		●		●	
TEMPERATURE	●		●		●								●		●		●	
CHEMICAL	●		●		●								●		●		●	

Note, PVC is shown but other plastic casings (ie, teflon) behave similarly.

quality, temperature gradient and hole diameter. Table 2.2 is a summary of borehole objectives and the methods used to achieve them.

Hardware for borehole geophysical logging consists of similar basic components for all the different tools, consisting of sensor, signal conditioners, and a recorder. The sensor or sonde receives power and transmits the signal to the surface through a conducting cable, which also serves to position the tool in the hole by means of a winch.

Electronic controls at the surface regulate logging speed and direction, power to the downhole electronics, signal conditioning, and recorder responses.

Two types of signal conditioning and recorder responses are available: analog and digital. Most systems that are equipped with digital processing and storage are also equipped with analog recording for purposes of backup and examination of the data during logging. The return signal from the probe is a function of lithologic, fluid, and borehole parameters and is recorded and later analyzed with a computer.

Electrical-magnetic logs

Electric and magnetic logs provide information about lithology, saturation, fracture location, fluid movement in the borehole and fluid conductivity. There are many types of resistivity and resistance tools in use.

Electric logs are a record of electrical potentials and resistivities. These logs can generally be run only in uncased holes that are filled with a conducting fluid. There are many types of electric logs which can be run in a borehole, the choice of which is dependent upon the purpose of the survey. Some electric logs make use of the natural electrical currents that exist under certain conditions. Most common is the spontaneous-potential (SP), which is described below.

Other electric logs induce a current to flow in the formation for the purpose of recording resistance and/or resistivity. There are numerous types of these logs, including single point and differential resistance, short normal, long normal, lateral, microlog, microfocus log, and the guard or lateral resistivity log. Each of these logs has a specific application, depending upon the lithology, depth of drilling mud invasion, and area of interest within the borehole. It is not necessary to run all of these electric logs to determine variations in lithology, aquifer locations, and relative conductivities of porous media fluids.

spontaneous potential--

The SP logs measure the small differences in natural potentials that develop in the borehole as a result of fluid movement and electrical potentials due to borehole fluid migration at lithologic contacts. SP logs can be used to delineate fault zones and water producing units in the borehole.

Keys and MacCary(1971) point out that the most important source of SP is due to the electrochemical electromotive force (emf) produced at the interface between dissimilar materials in the borehole. SP may also be generated in zones of gaining or losing water. The SP log can also be used to delineate relative hydraulic conductivities based on the knowledge of borehole fluid potentials. When the water within an aquifer unit is more conductive than the borehole water, the emf generated from the streaming potential or from the junction of dissimilar materials causes a current to flow from the borehole into that unit. As the SP electrode moves upward, it senses a decreasing potential because the current flows parallel to the

Table 2.2

BOREHOLE SENSING METHODS

OBJECTIVE	BOREHOLE METHODS
Location of Zones of Saturation	Electric Log (fully saturated) Temperature log Neutron log Gamma-gamma log
Physical and Chemical Characteristics of Fluids	Electric log Temperature log Fluid conductivity log Spontaneous potential log Specific ion electrodes Fiber optics D.O., Eh, pH probes
Stratigraphy and Porosity	Formation resistivity log Induced polarization log Natural gamma log Spectral gamma log Thermal neutron log Cross borehole radar Cross borehole shear Resistance log Acoustic - Transit time log Acoustic - Waveform log Neutron log Induction log Spontaneous potential log
Flow and Direction	Flow meter Tracer Differential temperature log Water level

well bore. This relationship would be reversed in the case of good quality water within an aquifer unit and one would see a positive SP response opposite the aquifer unit. Thus a negative or positive response on the SP log can be used to infer relative formation water qualities if the borehole fluid conductivities are known.

The electrode placement for SP logging is shown in Figure 2.2; one electrode is embedded in the surface material and the other is lowered down the hole. Figure 2.3 is a suite of simulated geophysical logs including SP indicating their response to different hydrostratigraphic units. A more detailed discussion of SP logging methods can be found in Hilchie(1982).

single point resistance--

Single point resistance logs measure the resistance to current flow of the borehole fluid and material. The logs are useful in geologic correlations because of their unique response to changes of lithology. Fractures or zones of weakness can be mapped with resistance logs, in addition to changes in borehole fluid conductivities. The resistance log can be used as a sensitive caliper log and as a water quality indicator. The SP and resistance logs are usually interpreted as a unit in any one borehole.

induced-current logging--

The methods previously described have required a conductive fluid because the current flows out into the formation directly from the electrodes. If it is necessary to survey a hole which contains a non-conductive medium such as air or hydrocarbon, electrical investigations can be carried out by inducing currents in the formations surrounding the borehole. This technique is called induction logging, and the theory is analogous to induction techniques used on the surface of the earth. This method can also be used in non-metallic cased holes.

Figure 2.4 shows a diagram of a conceptual induction tool. One coil is used for transmitting, the other for receiving. An alternating current of constant intensity is passed through the transmitter coil at a very high frequency. This electric field has an associated magnetic field which, in turn, induces electric currents in the formations. The phenomenon is linear for practical ranges of current levels, so the induced currents will be of the same frequency as the source current, but different in intensity and phase. Associated with the ground currents flowing around the hole is a magnetic field, which induces current to flow in the receiver coil. Of course, the magnetic field associated with the transmitter coil also induces current to flow in the receiver coil, but this can be filtered out by calibration procedures in an ideal known environment, e.g., air. In actual practice, the induction tool will have more than two coils, usually six or even more. Additional coils provide selective focusing of the transmitted signal so that the measurement is weighted away from the borehole environment and its effects. Figure 2.3 includes a hypothetical inverse induction log.

Nuclear logs

Nuclear logs measure radiation emitted from the nucleus of an atom and have a distinct advantage over most other geophysical logs in that they can derive information from cased or uncased holes that are filled with any type of fluid. The most common nuclear logs are natural gamma, gamma gamma, and neutron-neutron. The primary function of these logs is to determine variations in lithology, density, and moisture content or porosity within the borehole materials.

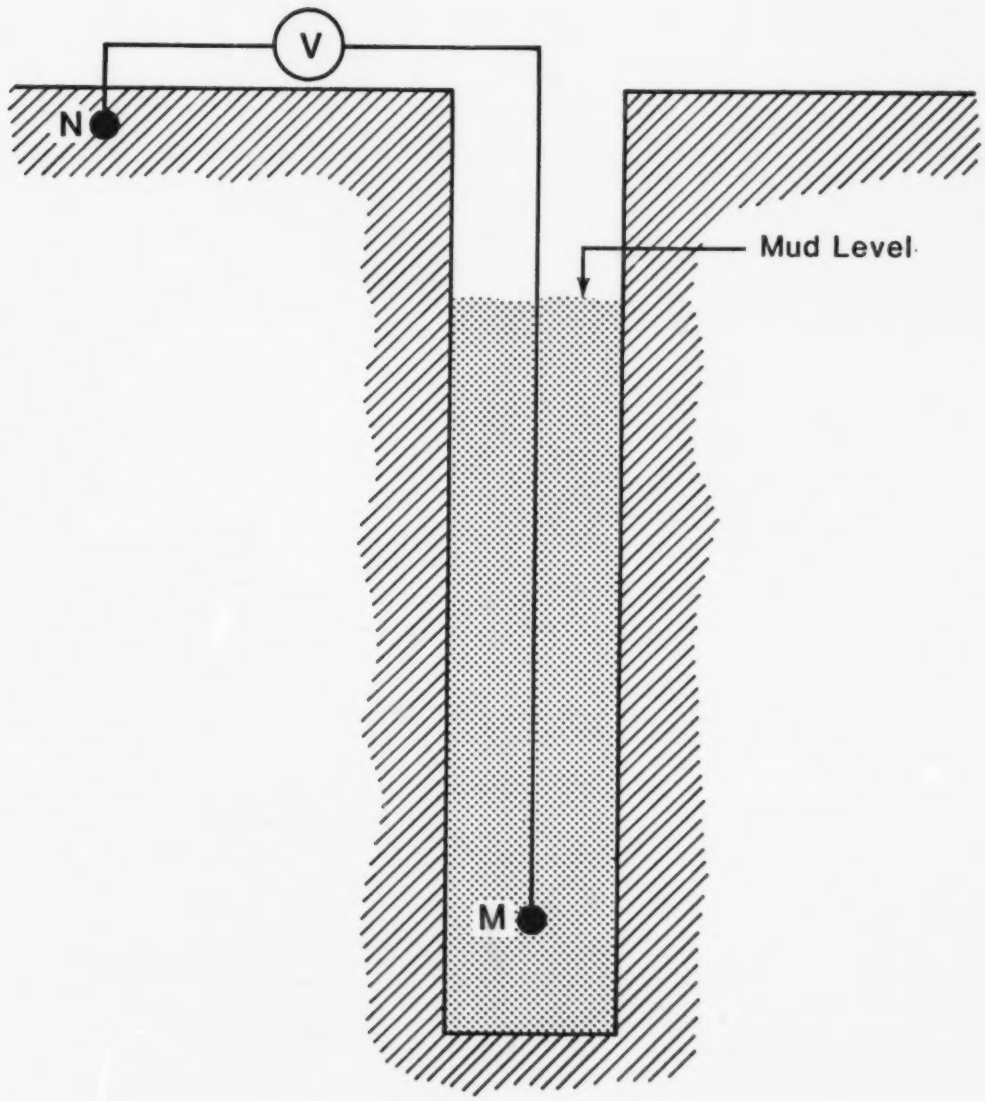


FIGURE 2.2. Electrode Placement for Spontaneous Potential Logging.

SIMULATED GEOPHYSICAL LOGS

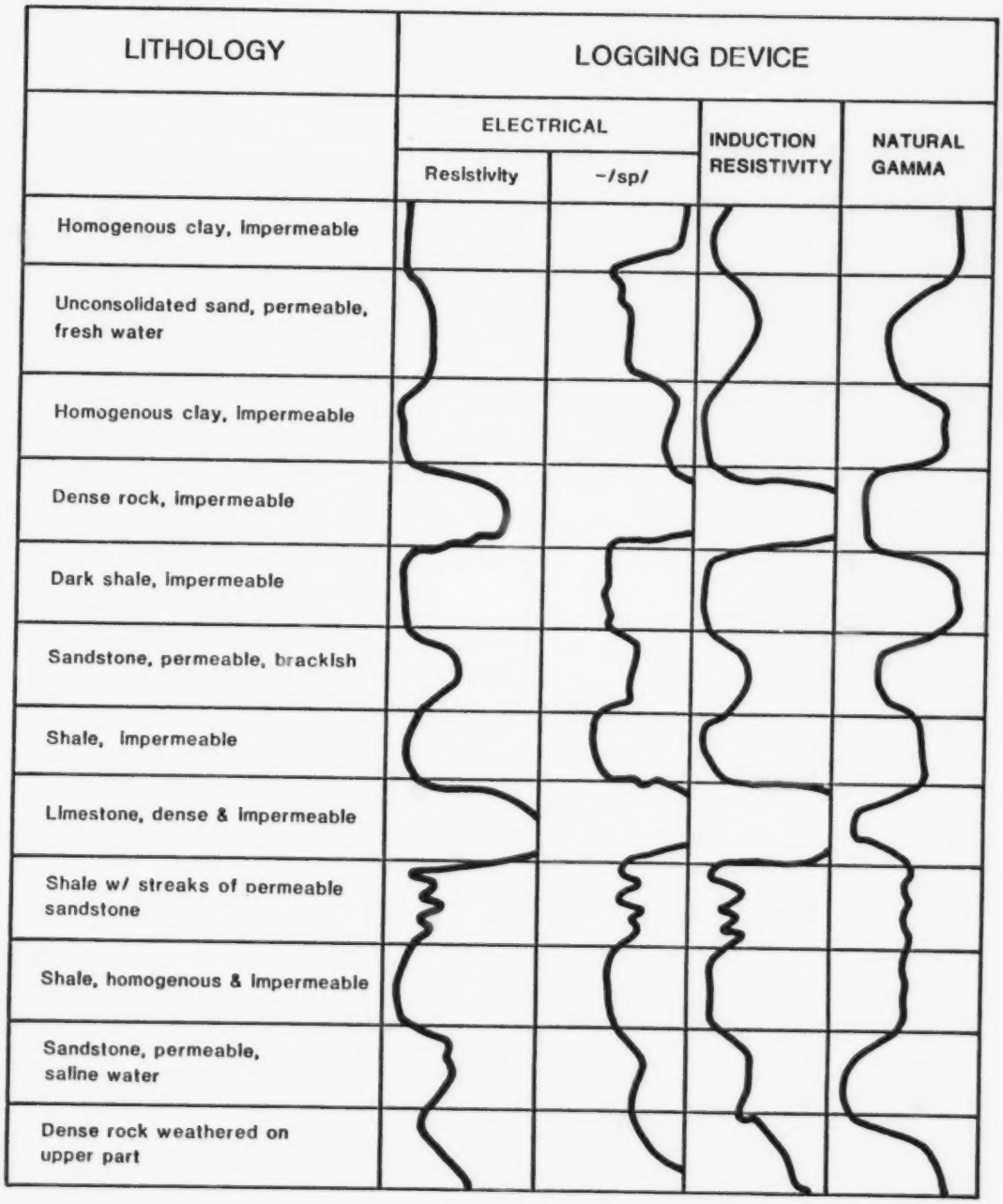


FIGURE 2.3. Simulated Geophysical Logs.

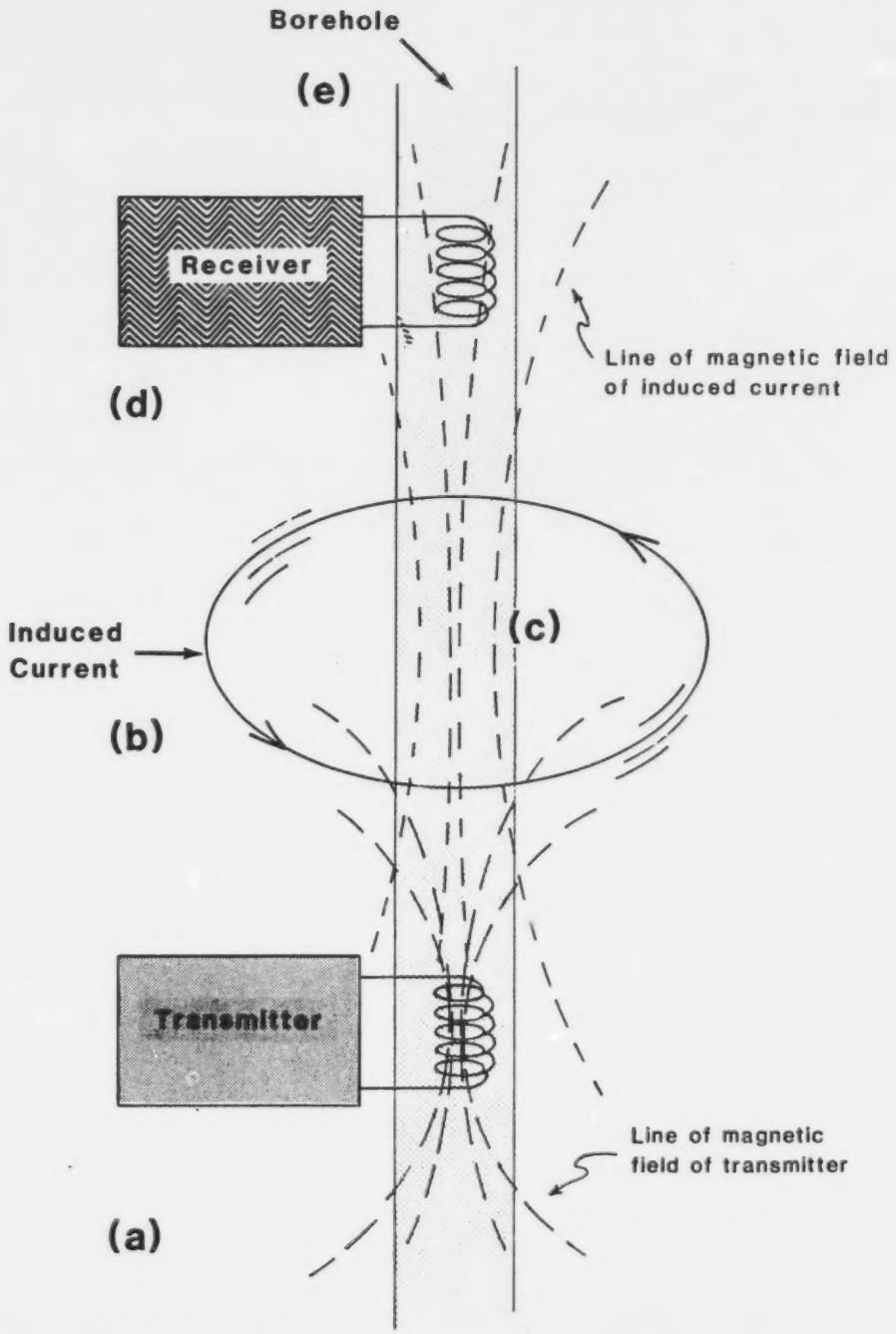


FIGURE 2.4. Schematic of Induction Tool Operating. The Transmitter and Receiver Coils are in a Borehole whereas the Induced Current is in the Earth.

gamma-ray logging--

This is a passive technique which uses a scintillation counter to measure the natural gamma radiation emitted by the materials in the vicinity of the sonde. Because the gamma ray emission is statistical in nature, it is appropriate to average the counts over time in order to obtain a stable value. The duration for averaging depends upon the level of radioactivity, lower levels requiring longer times. A few seconds are normally adequate in practice. Due to this averaging, any anomaly will be shifted in the direction in which the tool is moving.

Gamma-ray logging can be performed in a cased hole. If absolute values are desired, then corrections should be made for the density of the mud, the diameter of the hole, casing properties, etc.

Because radioactive elements tend to concentrate in shales and clays, the gamma-ray log is usually interpreted to indicate the shale content in sedimentary formations. A typical passive gamma-ray log is shown in Figure 2.3.

active gamma (gamma-gamma) logging--

In gamma-gamma logging the scintillation counter is packaged into a sonde with a radioactive source, as shown diagrammatically in Figure 2.5(a). The sonde is pushed against the sidewall to reduce or eliminate the effects of the mud. The source emits medium-energy gamma-rays which pass into the formation where they collide with electrons and are scattered. Some of these scattered gamma-rays are detected by the scintillation counter located at a fixed distance from the source. Thus, the active gamma-ray technique depends on the electron density of the formation. Since this is directly related to the bulk density of the formation, this technique is usually called the formation density log.

To circumvent the problem of correcting for the mudcake, a sonde with one radioactive source and two detectors can be used. Assuming that the mudcake conditions are the same at both the detectors, which are at different distances from the source, then the difference between the readings will be directly related to the formation electron density and, hence, the bulk density. The difference is independent of both the mudcake density and its thickness if both detectors encounter the same conditions. Such a sonde, having two detectors and one source, is depicted in Figure 2.5(b). This is called the Formation Density Compensated (FDC) tool.

neutron logs--

The configuration of the probe in neutron logging is oriented so that the tool responds primarily to a function of hydrogen content in the borehole environment. Neutron energy is modified by elastic collisions with borehole elements and the effectiveness of these energy moderators is a primary factor in neutron logging. The mass of the nucleus of a hydrogen atom has approximately the same mass as the neutron, so a collision of a neutron with a hydrogen atom causes the neutron maximum energy loss.
Consequently, the energy of the neutron response is interpreted for moisture content in the unsaturated zone of the borehole and the total porosity below the water table. Neutron logs can show the location of porous aquifer units, perched water tables, and ground-water confining zones, such as clay layers.

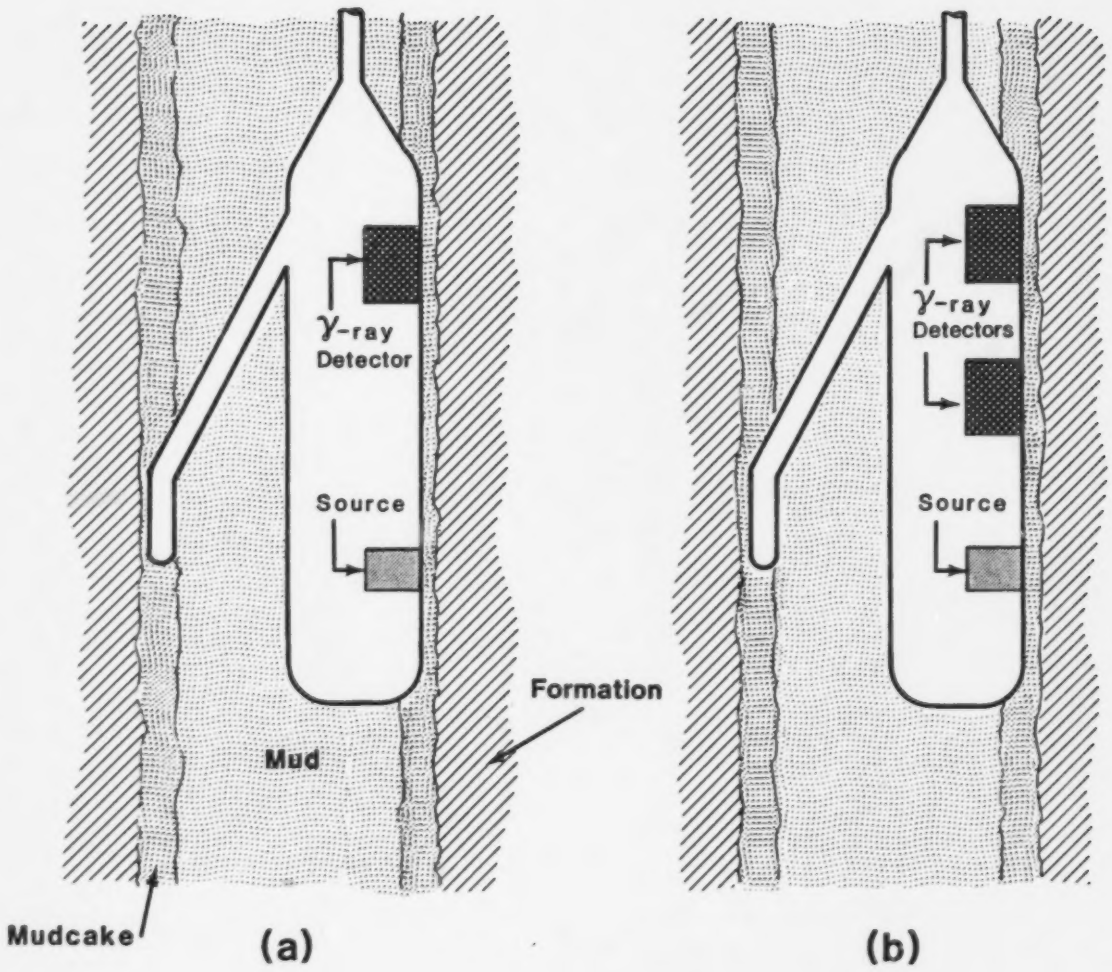


FIGURE 2.5 Schematic of Formation Density Compensated Sonde (b); Original Design shown in (a).

Acoustic logs

The ability of a rock to transmit acoustical waves is a measurable rock property that is useful in determining related properties of interest such as porosity and fracturing. The most commonly used acoustical wave for these studies is a pressure wave that is generated by a source in the borehole. In the simplest of tool designs, this wave is detected at a receiver located in the borehole which is a short but constant distance from the source. Although many travel paths occur, the instrument is set to record only the wave which is refracted through the formation. Currently, instrumentation is available to measure both seismic velocity and the full seismic waveform.

Seismic velocity, as measured by borehole methods, is the speed at which a vertical traveling pressure wave propagates and is dependent on the elastic properties of the formation. Since rock material and fluids have such vastly different elastic properties, the presence of fluids will greatly effect the velocity. Wyllie(1956) derived an empirical relationship between porosity and velocity:

$$\frac{1}{V_a} = \frac{n}{V_f} + \frac{1-n}{V_m}$$

where

V_a = measured acoustic velocity

V_m = matrix acoustic velocity

V_f = pore fluid acoustic velocity

n = porosity

The matrix velocity (V_m) is the acoustic velocity within the matrix of the formation. Since this is nearly a constant for most common earth materials, its value can be assumed. Pore fluid velocity (V_f) can also be assumed because it is nearly constant for water. Hence using this equation, the porosity can be determined. The advantage of using an acoustic tool to measure porosity instead of a tool with a radioactive source is the logistical simplification of eliminating the radioactive source.

Acoustic amplitude can also be recorded by some equipment. This equipment normally records the full pressure waveform. Discontinuities in the formation such as fractures, will influence the waveform amplitude. Although it is not currently possible to quantify fracture patterns using the waveform amplitude, at least an indication of fracture occurrence can be obtained.

Acoustic logging is commonly done in an open hole. The presence of a casing creates another travel path for the seismic energy and the instrumentation must be able to distinguish the arrival through the casing from the arrival through the formation.

Variations in borehole diameter will significantly effect both velocity and amplitude measurements. Hence most tools employ two transmitters, one located above and one below a pair of receivers. This geometry allows processing of the signals so as to minimize errors due to variations in the borehole diameter.

Temperature logs

The temperature in a shallow well can easily be measured using an appropriate thermistor. This temperature may be used to correct other observed data, such as the conductivity log and the resistivity log. The temperature log can also be used to indicate borehole intervals that are producing or accepting fluids. This may be helpful in locating zones for more detailed flow measurements with a borehole thermal flow meter (discussed in Section 5).

Televiewer

This tool is simply a television camera which is used to look at the interior of the borehole and/or well casing. It can delineate and correlate fractures if used prior to casing installation. For wells in which there is no casing information, the televiewer is useful for inspecting perforations or slotting and determining their frequency and orientation. Slotting information is necessary to properly use the thermal horizontal flow meter discussed in a later section.

Multiple hole techniques

Multiple hole techniques require several holes for implementation. Seismic methods are commonly used between boreholes. A seismic source is placed in one hole, and seismic signals are received in one or more other boreholes (Gal'perin, 1974). By placing source and receivers at different depths in different holes, complex three dimensional interpretations are possible.

Borehole-to-borehole radar is another commonly used multiple hole method. Operationally, this method is similar to the multiple hole seismic techniques, with the seismic source and receiver being replaced by an electromagnetic transmitter and receiver.

Nontraditional subsurface sensing

In addition to the traditional logging methods developed by the petroleum and mineral industries, there are a number of sensing techniques that can potentially provide valuable information for hazardous waste site investigations. Non-traditional techniques include geochemical, thermal, moisture and vapor sensing methods. Of particular interest is the ground-water flow meter which senses ground-water flow by induced thermal pulses. This instrument is discussed in detail in Section 5. Sensors for many of these methods can be left *in situ* for continuous monitoring with time. Table 2.2 presents a list of methods applicable to measuring different properties of interest in hazardous waste site investigations and monitoring.

In situ methods may prove to be particularly useful for the problem of contaminant plume monitoring. Long term monitoring of borehole parameters will provide information on the variance of the monitored parameters (from a stochastic point of view) and long term trends of increase or decrease of the parameters. For many of the *in situ* methods, little additional cost is incurred to collect the data, once the instrumentation is in place.

SECTION 3

LIMITATIONS OF BOREHOLE METHODS FOR HYDROGEOLOGIC INVESTIGATIONS

INTRODUCTION

From the information provided in Section 2, it should be evident that considerable problems are encountered when trying to apply existing borehole methods to the hydrogeologic investigations at hazardous waste sites. The problems arise primarily from two considerations:

1. The typical environment in which borehole methods are commonly used in the petroleum industry is very different than the environment that commonly exists at hazardous waste sites.
2. The petroleum industry obtains information from the borehole logs that is quite different from the information sought by the hydrogeologist for hazardous waste sites.

EQUIPMENT LIMITATIONS

The design considerations for borehole logging equipment have primarily been set by the petroleum and mineral industry and are a direct result of the environment that the equipment must function in. It is useful to contrast and compare the "typical environment" for a petroleum well and a well installed for monitoring a hazardous waste site.

Oil wells are nearly always deep (hundreds to thousands of meters). Logging is done immediately upon hole completion and often before completion, the hole is logged to aid in determining how much further to drill. Once the hole is logged upon completion, it is seldom logged again. Most oil wells are at least 30 cm in diameter. The hole is filled with mud during logging, and the mud has infiltrated into the formation.

There are a number of common aspects regarding the design of borehole equipment for these environments. The downhole sondes must be able to withstand high pressure and temperature because of the depth. Several logging tools are commonly installed in one long sonde. This is done for two reasons: the large depths coupled with the desire to obtain a multi-log suite; and the need to obtain multi-log suites that can be accurately correlated for depth with respect to each other. Multi-log sondes can be as much as 5 m in length. For a 5,000-m borehole, a 5-m long sonde can be considered to be essentially a point. Many of the logging tools will only work in an open hole. Table 2.1 summarizes the kinds of environments that

various types of logging tools can be used in.

The typical borehole that exists at (or around) hazardous waste sites is shallow (probably less that 100 m and typically about 30 m), narrow diameter (5 cm) and cased, usually with PVC, teflon, or some other plastic. None of the borehole tools that have been designed for petroleum well logging are usable in such an environment. Although a 5 m sonde would fit in a 30 m borehole, its upper most tools would miss logging the bottom portion of the borehole. Unless the hole has not been cased, none of the open hole tools such as the electric logging tools, can be used. If the tools could be used, they would be over-designed for temperature and pressure requirements, however the hazardous waste site ground water may contain chemicals for which the sonde was not designed to withstand.

LIMITATIONS OF INTERPRETATION SCHEMES

Most of the interpretation schemes that have been developed have been for open hole logging. The emphasis is on eliminating borehole mud and mud filtrate effects from the data, and trying to determine formation contacts and other parameters that are useful to the petroleum reservoir engineer. The parameters that are of interest to the petroleum industry are discussed in Section 2. The parameters that are of interest to the hydrogeologist are delineated in Section 4, along with an interpretation strategy to obtain them.

SECTION 4

BOREHOLE LOGGING INTERPRETATION STRATEGY FOR HYDROGEOLOGISTS

INTRODUCTION

The oil and mineral industries have been collecting and interpreting borehole logging data for many years. The interpretation strategies that have been developed are naturally oriented towards solving problems and answering questions that are of interest to these disciplines. Borehole logging data are potentially of great value to hydrogeologists for evaluating hazardous waste sites. However, new interpretation strategies must be developed that are designed to provide quantitative information on the formation parameters that are of hydrogeologic interest.

There is some overlap in the interests of the hydrogeologist and those of the oil or mineral geologist. However, the collection and interpretation of logging data requires a complete re-thinking in order to maximize the information that is useful for the study and prediction of contaminant transport in aquifers.

The vertical variation in hydraulic parameters within an aquifer is recognized to be of primary importance in determining the fate and transport of contaminants in ground-water systems. Traditionally, the process of hydrodynamic dispersion has been thought to be the dominant process causing contaminant mixing. Macro-scale heterogeneity and vertical stratification induce large variations in the advective flow rate of the ground water. This process has been termed macroscopic dispersion (Schwartz, 1977; Smith and Schwartz, 1980), and it is the dominant mechanism controlling contaminant mixing and transport in many aquifers.

Largely because of macroscopic dispersion, traditional techniques of vertical integration (Bear, 1979, Chapter 5) to derive two-dimensional vertically-averaged ground-water flow equations are inadequate to describe contaminant transport in aquifers. Although it is important to account for vertical variation in hydraulic parameters, there has been little effort to develop adequate borehole methods that would provide such parameters. Aquifer parameters that are important for contaminant transport studies include: lithology, effective and total porosity, tensor hydraulic conductivity, fluid velocity, cation exchange capacity, aquifer dispersivity and total organic carbon.

In a general sense, geophysical methods applicable to hazardous waste site investigations can be divided into two categories: subsurface methods and surface methods. Surface

methods have the advantage of not requiring a borehole and in general a large horizontal area can be quickly covered. Unfortunately, the interpretation of surface methods is often ambiguous and additional information is usually required.

Subsurface methods require a borehole and can only investigate an area immediately around the borehole. They do however provide excellent information on vertical changes and because of the wide variety of complementary measurements which can be made, they can provide a great amount of information. Obviously, the two approaches complement each other nicely. The subsurface methods provide the necessary detail but only in a small area, and surface methods extend this detail in the horizontal directions. This is not to say borehole methods do not have pitfalls but that an integrated approach of surface and borehole geophysics along with more conventional techniques is desirable.

OBJECTIVES

The purpose of this section is to outline a borehole logging interpretation strategy for hydrogeologists for use in the saturated zone. The development of a similar strategy for the unsaturated zone may be part of a proposed future cooperative agreement. The objectives of the strategy are:

1. Select a suite of logging tools that can be used to obtain the hydraulic parameters necessary for contaminant transport studies.
2. Develop a technique to quantitatively combine the information from the selected logging tools so that the hydraulic parameters and their vertical variations can be obtained for a specific hazardous waste site.

Originally, the strategy was to be tested in the field, but due to factors beyond the control of DRI and EPA, the logging equipment to do the testing was not available. The field testing, and refinement of the strategy may be an important part of a proposed future cooperative agreement between EPA and DRI.

HAZARDOUS WASTE SITE INVESTIGATIONS

Before a strategy can be developed, it is important to understand the environment in which it will be used. Typically wells are shallow and details of perforations and mud logs are poor or unreliable. Unlike traditional logging which is done in uncased holes just after hole completion, logging at hazardous waste sites will normally have to be done in PVC-cased holes with short perforated intervals. Usually there are several wells in a relatively small area which were initially drilled for monitoring but which can be used for borehole geophysics. Typically the site has an abundance of cultural activity which restricts the use of some surface geophysical methods.

If borehole methods are to be of use for hydrogeologists, it is essential that they answer questions of hydrologic significance. In particular this strategy strives to describe how the following parameters vary with depth: effective and total porosity; tensor hydraulic conductivity; lithology; ground-water velocity; cation exchange capacity of the formation; and electrical conductivity of the pore fluid.

It is necessary to have a clear understanding of how to get from the measurements taken in the field to our desired goals. The exploration industries have developed sophisticated

strategies to do this, but because they operate in different environments and have different goals, many of their well-developed and tested strategies cannot be applied to hazardous waste site investigations. While relying on the same principles it is necessary to develop modifications of equipment, field techniques and interpretation strategies. The following sections explain a strategy which can be applied at a hazardous waste site.

SITE CHARACTERIZATION

Hazardous waste sites are located in every conceivable geologic setting. Each one is unique and relationships developed for one site cannot be considered valid elsewhere. It is essential that relationships used in interpretations be based on data collected at the site under study. To do this, it is necessary to drill characterization holes at each site.

The characterization holes should be drilled with a technique than allows good core samples to be taken. These cores will be analyzed for lithology, hydraulic conductivity, effective porosity, and cation exchange capacity. This information will be combined with the well logs of the hole to provide the necessary site specific relationships for interpretation of the other wells from which cores are not available. Although the characterization wells do not provide an absolute calibration of the logging tools, it permits the tool response to be related to the local conditions.

Obviously, the characterization holes must be representative of the site. It may be necessary to have several characterization holes and different relationships must be developed in different formations if the geologic environments were significantly different during their formation. Because most hazardous waste sites are small and the geologic processes that formed them are usually consistent across them, the extrapolation of relationships across the site is usually valid. By comparing the relationships developed for a given unit with data from different wells the validity of this assumption can be checked.

INTERPRETATION STRATEGY

This strategy combines the geophysical information from the well logs and the geologic information from the characterization well to answer the hydrologic questions of interest. Figure 4.1 shows a block diagram of the strategy and the reader is urged to refer to it frequently. The strategy is only developed for use in the saturated zone. Additional strategies for use in the unsaturated zone will be developed as part of a future cooperative agreement.

Porosity

The gamma density log which measures the bulk density of the formation can be used to determine porosity if matrix density is known. The relationship is derived from the fact that the bulk density is a weighted average of the density of the formation's constituents:

$$\rho_B = n\ \rho_f + (1-n)\ \rho_m \tag{4.1}$$

and is

$$n = \frac{\rho_B - \rho_m}{\rho_f - \rho_m} \tag{4.2}$$

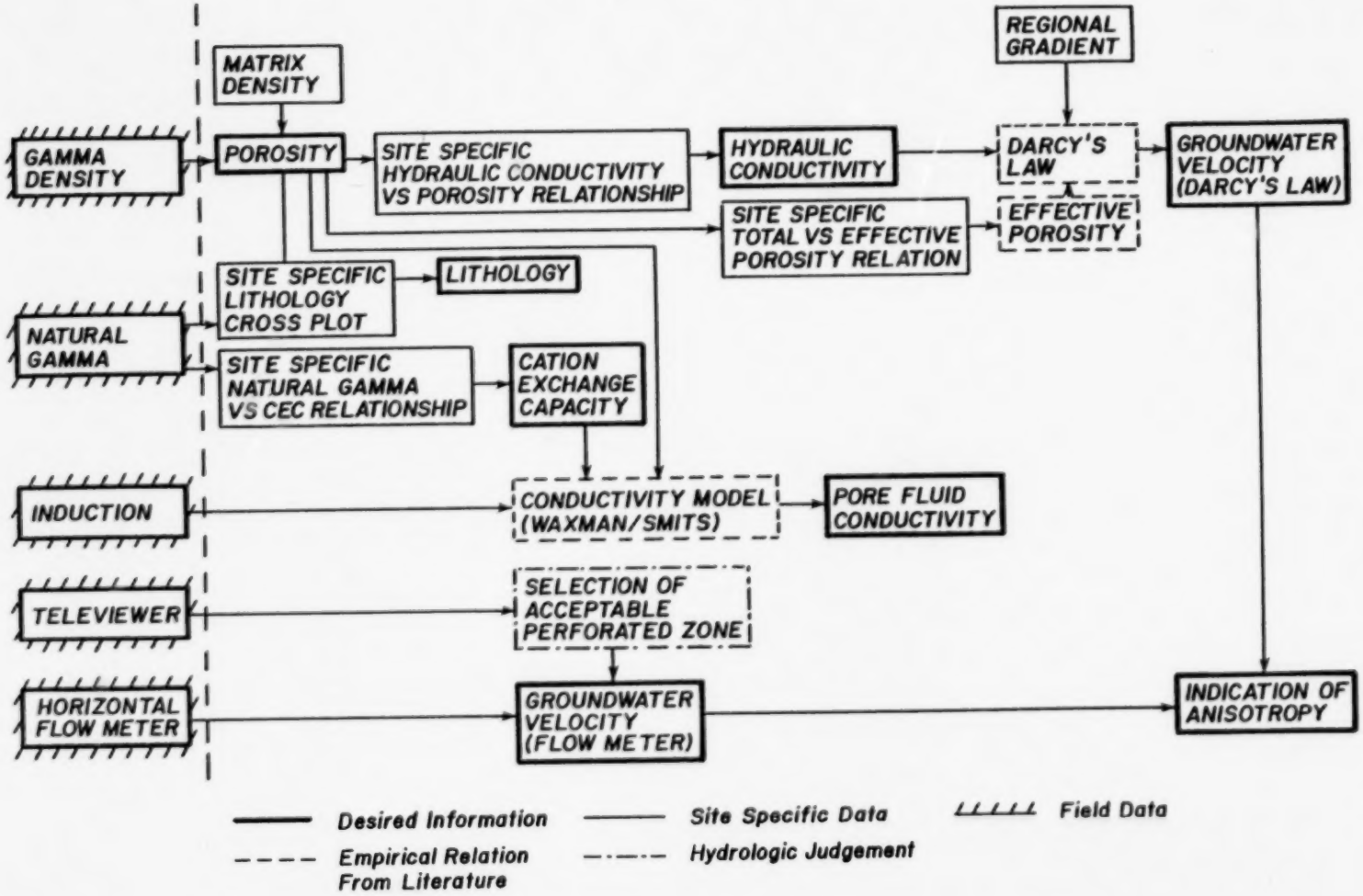


FIGURE 4.1. Interpretation Strategy.

where

n = total porosity

ρ_B = bulk density (from density log)

ρ_m = matrix density $\approx$ 2.65 gm/cm^3

ρ_f = fluid density $\approx$ 1.0 gm/cm^3

The choice of a matrix density, which is the density of the formation material excluding the pore space and fluid, is determined by noting the mineralogy in the core samples. Once the mineralogy of a particular formation is known its matrix density can be calculated from a weighted average of the density of the matrix minerals.

Effective porosity differs from total porosity in that it is the percentage of total pore space available for fluid transport. Fluid in pore spaces that are dead ended (vuggs) or extremely small (clays) is not mobile and hence this pore space is not included in effective porosity. In coarse sediments with inter-granular porosity, effective porosity will be the same as total porosity, but as the percentage of dead end pores increases or pore size decreases, effective porosity will become less than total porosity.

The core samples from the characterization wells can be evaluated to determine if there is a significant difference between effective and total porosity. This can easily be done with a tracer test when the cores hydraulic conductivity is determined. If there is a significant difference, it is necessary to attempt to develop a site and formation specific relation between the two. If this can be done then an effective porosity log can be obtained by applying the relationship to the total porosity log.

Hydraulic conductivity and regional ground-water velocity

There are two possible ways to obtain hydraulic conductivity and ground-water velocity. Both methods have advantages and disadvantages and when used together, they can yield information on the hydraulic anisotropy of the formation.

The most direct way of obtaining hydraulic conductivity and velocity is with a borehole thermal ground-water flow meter. The use of this device for measuring fluid velocity and hydraulic conductivity, along with its limitations, is discussed in detail in Section 5.

An alternate method of determining hydraulic conductivity is based on the more conventional logging tools. The first step is to determine the hydraulic conductivity of many short sections in several of the boreholes. This can be done by analysis of core samples or hydraulic tests of short borehole intervals. The intervals investigated must be representative of the range of conductivities in the formation. To investigate the possibility of a relationship between hydraulic conductivity and porosity the conductivity of each interval is plotted against the log derived porosity that corresponds to that interval. Riclo (1962) has demonstrated such relationships for shallow sediments with intergranular porosity. It is important to keep in mind the relationship, if it exists, will only be valid for the formation and locality from which the data was obtained. The relationship tends to occur because with in a given depositional system any change in sorting, the controlling factor for porosity, will also be

accompanied by a change in grain size distribution, the controlling factor for hydraulic conductivity. Various statistical approaches can be used to quantify the relationship and used to predict the hydraulic conductivity that corresponds to a given porosity. This relationship is then applied to the porosity logs and a corresponding hydraulic conductivity log can be obtained.

Once the hydraulic conductivity logs have been obtained, this information along with the effective porosity log and the regional gradient can be used to find the pore velocity from Darcy's Law.

It is important to understand the limitations and assumptions used in these two methods for obtaining ground-water velocity information. The flow meter technique requires a well with acceptable perforations. A televiewer is commonly used to determine if this condition exists. There are also restrictions on the minimum velocity that can be measured. The porosity relationship approach is dependent on the development of a porosity versus hydraulic conductivity relationship which may not be as unique as desired.

Hydraulic anisotropy

In addition to direct measurement of hydraulic conductivity, the thermal flow meter can be modified to directly measure the velocity direction. The result is that the flow meter can be used in conjunction with the regional and local piezometric head gradient to obtain the true hydraulic conductivity for an anisotropic aquifer. For an anisotropic aquifer, the hydraulic conductivity is a second rank tensor, and the direction of flow is (in general) different from the direction of the gradient.

The direction of flow (Θ_q) is a function of the gradient direction (Θ_j) and the principle values of the hydraulic conductivity tensor, K_{xx} and K_{yy}, where x and y are the coordinate axes of the principle directions. Figure 4.2 shows the relationships and definitions of the variables. For more information on anisotropy, see Bear (1979, chap. 4). The relationship between Θ_q and Θ_j is determined by using trigonometry and Darcy's Law:

$$\Theta_q = \tan^{-1}\left(\frac{q_y}{q_x}\right) \tag{4.3}$$

where

$$q_x = K_{xx}\, J_x \; ; \; q_y = K_{yy}\, J_y \text{ (Darcy's Law)} \tag{4.4a,b}$$

and

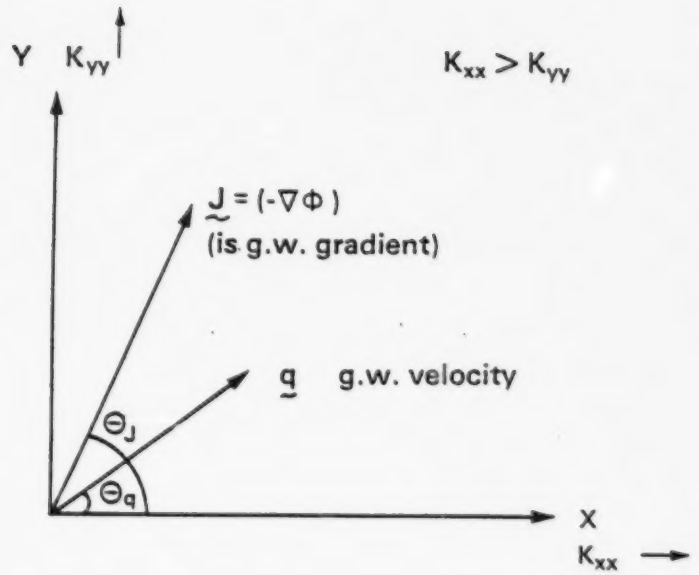
$$\vec{J} = \vec{i}\, J_x + \vec{j}\, J_y \; .$$

Substituting eq. (4) into (3) and using $J_x = J\cos\Theta_j$ and $J_y = J\sin\Theta_j$, we have:

$$\Theta_q = \tan^{-1}\left(K_r \tan\Theta_j\right) , \tag{4.5}$$

where $K_r = K_{yy}/K_{xx}$.

The importance of determining anisotropy cannot be overemphasized. As an example, assume that the direction of the gradient is 30 degrees from the x-axis and $K_r = 2$, then using eq. (4), the velocity direction would be nearly 50 degrees. In other words, changing the conductivity ratio by a factor of two can change the velocity direction by as much as 20 degrees.



$$q_x = -K_{xx} \frac{\delta\Phi}{\delta X}$$

$$q_y = -K_{yy} \frac{\delta\Phi}{\delta y}$$

$$\Theta_q = \tan^{-1} (K_r \tan \Theta_J)$$

$$\text{Where } K_r = \frac{K_{yy}}{K_{xx}}$$

FIGURE 4.2 The Relationship Between the Velocity and the Gradient for an Anisotropic Aquifer.

Therefore, the degree of anisotropy has significant implications for the placement of down-gradient monitoring wells and the prediction of contaminant plume migration.

Lithology

Borehole methods are of great help in determining lithology. If a plot is made with porosity on one axis and the corresponding natural gamma response on the other axis it may be found that formations with similar lithology will form groups on the plot. Figure 4.3 is an example of this concept. The core and geophysical data from the characterization holes can be used to make such a crossplot.

This is done by plotting the lithology of numerous samples from the characterization wells on the crossplot. If enough samples representative of the different lithologies are available, it will be possible to define the lithologic boundaries on the crossplot. Once the crossplot is defined, the unknown lithologies in wells from which core data is unavailable can be determined by plotting the natural gamma and porosity response on the crossplot and noting in which lithology field it plots.

Cation exchange capacity

The cation exchange capacity (CEC) of the formation is important because it significantly affects the mobility of some contaminates and affects the geochemistry and electrical properties of the formation and pore water. CEC is primarily a function of clay content and type. It is closely related to the natural gamma response because formations with high CEC preferentially absorb high valence cations including U^{+4} and Th^{+4}. Naturally occurring radioactive isotopes of these cations frequently account for the majority of the radiation associated with clays. In some environments the Potassium in the clay matrix will be the dominant source of radiation (Donovan and Hilchie, 1979, Johnson and Linke, 1977). The cores from the calibration well can be analyzed for CEC and a statistical correlation can be made to the natural gamma log. From this relationship, the CEC corresponding to a given natural gamma response can be determined. This relationship, if it exists, can then be applied to all the holes and CEC logs can be obtained.

Pore fluid electrical conductivity

Electrical conductivity of a fluid is closely related to the ionic strength of the solution and in many, but not all, instances can be an indicator of contamination. Unfortunately, it is not possible to directly measure the electrical conductivity of the pore fluid. The fluid in the well is a mixture of fluids and has been exposed to the atmosphere and hence is not necessarily representative of the actual pore fluid. It is desirable to have a method of measuring the *in situ* pore fluid conductivity.

The induction log measures the electrical conductivity of the formation, but this is influenced by many things. Current in the formation is conducted by two major pathways; through the pore fluid and by ion movement along surface exchange sites. In general the matrix does not contribute significantly to the electrical conductivity.

To determine the pore fluid conductivity, it is necessary to quantify these effects. The path through the pore fluid is affected by pore fluid conductivity and porosity. The surface path is controlled by the number of exchange sites that are available for ion movement and hence is related to CEC.

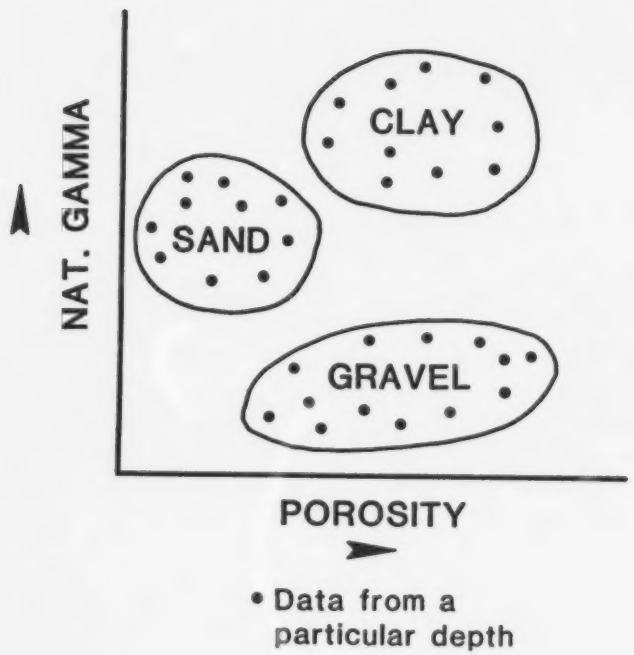


FIGURE 4.3 Lithology Cross Plot.

In clay free formations, the number of exchange sites is negligible and the surface path can be ignored. Under this situation, Archie's Law (Keller and Frischknecht, 1966), expressed here in conductivities can be used to express the relationship between n, σ_b, and σ_f:

$$\sigma_b = \frac{n^m \sigma_f}{a} \tag{4.6}$$

where

σ_b = bulk conductivity (from induction tool)

σ_f = fluid conductivity (unknown)

n = porosity (from density tool)

a = tortuosity $\approx$(0.62–1.0)

m = saturation exponent $\approx$(2.0–2.15).

The values for a and m have been empirically obtained and are dependent on lithology.

The porosity can be obtained from the density log as explained in Section 5.1, and the induction log measures σ_b. Archie's Law can then be applied and an *in situ* pore fluid conductivity log obtained.

If clays are present, the surface conductance along the surface of the clays cannot be neglected and it is necessary to use a model such as that proposed by Waxman and Smits (1968):

$$\sigma_b = n^m (B\ Q_v + \sigma_f) \tag{4.7}$$

where

$$B = 0.046\ [1\text{–}0.6\ \exp\text{–}(\sigma_f / 0.013)]$$

$$Q_v = \frac{CEC\,(1\text{–}n)\ g\ \rho_B}{100\ n}$$

CEC = cation exchange capacity, meq/100gm (from CEC log)

ρ_B = bulk formation density (from density log)

In this equation, σ_f is the unknown, σ_b is obtained from the induction log, and n is obtained as in Section 5.1. Density is measured with the density log, and knowing the lithology, m can be obtained from the literature (Keller and Frischknecht, 1966). CEC is obtained from the natural gamma log as explained in Section 5.5. The term $B\ Q_v$ is the additional conductivity

from surface conductance. Using this equation to relate the log data, pore fluid electrical conductivity can be determined.

It is important to emphasize that this method allows the measurement of an *in situ* profile of pore fluid conductivity that uses the CEC log to account for the influence of clays. It is not necessary to determine the clay type or amount because only the CEC which is obtained from the natural gamma log is necessary.

COMPUTER IMPLEMENTATION

Large data sets and nonlinear relationships make computer processing a necessity. It is desirable to record the data digitally, but if only a limited number of sites are investigated and turnaround time is not critical, the analog data could be recorded and digitized later.

The processing software would only require a microcomputer and a plotter. The software can be written to guide the interpreter through the strategy, and perform the important task of keeping track of the propagation of uncertainties. It is not desirerable to reduce the software to a standardized package as this would encourage users not to take the time to fully understand the assumptions in the processing sequence. This software package could be readily used by small firms. The actual field work could be contracted out, thus eliminating the need of a high capital equipment cost.

FURTHER REFINEMENTS

Effects of drilling disturbances

All drilling techniques will disturb the formation in the immediate vicinity of the well. The effect this will have on the interpretation is dependent on the degree and depth of disturbance, and the effective penetration of the logging measurements. If two gamma density logs are made with two different source detector spacings, thereby allowing measurement of formation density weighted over two different horizontal distances from the borehole, an indication of drilling disturbances can be obtained. Under favorable conditions, the drilling effects can be removed from the density measurement or at least intervals of significant disturbances can be identified and treated with an alternate approach than is suggested here. In theory the same concept could be used for the induction tool, but a small diameter multiple spacing induction tool is not currently available.

Tool response

Logging instrumentation does not make a measurement at a point, but because of practical design restrictions, the value is a weighted average over a short section of the borehole. This spatial average varies depending on the tool design. It is important that when logs are compared from different tools that the measurements are weighted averages of the same section of the well. This is particularly important near thin beds and abrupt contacts.
The effects of different spatial averaging can be removed by digital filtering of the data so that the two measurements are averaged over the same interval, or in some instances by deconvolution, a digital process which removes the effects of spatial averaging.

Improved electrical conductivity model

The calculated pore fluid electrical conductivity is strongly dependent on the way the matrix properties are accounted for. Because clay-bearing formations will have a frequency dependent electrical conductivity (Ward and Fraser, 1967) it is important to have a model that is accurate at the measurement frequency. Field tests of this strategy will be done with a Geonics EM-39 which operates at a frequency of 50 KHz. Unfortunately, conductivity starts becoming strongly frequency dependent at around 50 KHz and above. Therefore, the Waxman/Smits model is not wholly acceptable much above this frequency; it would be useful to develop a better model.

There are major instrumental difficulties in measuring conductivities of reasonable sized lab samples at 50 KHz. The Waxman/Smits model can be used but it is important to be aware of its possible pitfalls in high clay content formations. Additional thought should be given to developing a practical set of experiments from which an improved model could be developed.

Effects of contaminants

This strategy assumes that the site specific relationships obtained from the calibration well hold throughout the site. Although different relationships could be developed for different formations it is assumed that these relationships are valid throughout the formation for which they were developed. In unusual cases, it is possible that the presence of the contaminant could alter these relationships and invalidate the interpretation. Because these relationships are based on fairly simple physical and chemical principles, a review of the literature along with an understanding of the mechanisms involved may make it possible to identify conditions where the contaminant might be altering the relationships used in the interpretation.

CONCLUSIONS

A strategy has been developed that combines selected traditional borehole logging techniques with hydrogeologic borehole equipment and methodology. When the strategy is applied as outlined in this section, the parameters that are important to contaminant plume detection, monitoring and transport prediction can be calculated for every borehole located in and around the hazardous waste site. Because logging gives information with respect to depth, the strategy provides these parameters as a function of depth in the aquifer. The parameters that can be obtained from this strategy include lithology, total porosity, effective porosity, ground-water velocity, hydraulic conductivity (including anisotropy), cation exchange capacity and pore fluid conductivity.

Considering the wide range of conditions present at hazardous wast sites it is not possible to develop a universal technique that will work everywhere. The interpretation strategy presented here relies heavily on the use of core data to determine site and formation specific relations between measured parameters and parameters of interest. Although the relations used here have been noted in some geologic environments this does not imply that they will always be present. However when they are it desirerable to take advantage of them, when they are not an alternate approach must be employed. Although the strategy can be reduced to a simple set of computer programs the processing and interpretation must always by done by an individual who understands the significance of both the hydrologic and geophysical assumptions and relations that are made along the processing path and can decided if they

are appropriate.

Macroscopic variations in hydraulic parameters are the most important contribution to contaminant mixing and dispersion in aquifers. This strategy is designed to provide sufficient detailed information so that the mixing and dispersion process can be modeled by strictly advective transport processes. This is an attractive alternative to using advective-dispersion models which require complex field experiments to determine dispersion coefficients and still often require trial and error calibration.

Under a proposed cooperative agreement with EPA, DRI will evaluate this strategy at a number of field sites. Refinements will be made to it based on the field experience.

SECTION 5

USE OF A BOREHOLE THERMAL FLOW METER FOR DETERMINATION OF GROUND-WATER VELOCITY AND HYDRAULIC CONDUCTIVITY

INTRODUCTION

Subsurface data are required to determine hydrogeologic conditions of hazardous waste sites, to locate contaminant plumes, and to monitor for leaks from disposal and storage facilities. Ground-water velocity is the most important information to help determine direction of contaminant plume migration. Ground-water velocity is a vector, possessing a speed (magnitude) and a direction. It is needed to locate the up and down gradient monitoring wells and to estimate potential contaminant pathways and travel times.

The traditional way of determining ground-water velocity is to calculate it using Darcy's Law and regional or local piezometric head gradient information. This is an indirect measurement, and does not take into account velocity variations in the vertical dimension. A more desirable method to obtain velocity information in principle would be to directly measure it in a borehole. One way of doing this is with a thermal ground-water flow meter.*

The ground-water flow meter evaluated in this study is the KV Associates Model 30L Geo-Flo. The instrument operates by inducing a heat pulse and monitoring the pulse movement away from the source. The following section will describe in detail the theory of instrument operation.

It is necessary to understand the instrument before discussing the specific objectives of this study, but the general goals are to determine the instrument limitations and accuracy; and evaluate the manufacturer's suggested calibration procedures. In addition, theoretical work will be presented to show that there is an alternative to the empirical calibration and that it is possible in theory to use the instrument to determine the hydraulic conductivity of the aquifer, in addition to the ground-water velocity.

*It would be more appropriate to call the instrument a ground-water velocity meter, but the term flow meter is in widespread use, so we use the same terminology.

DESCRIPTION AND THEORY OF OPERATION

The probe itself consists of a central heat source surrounded by five pairs of thermistors. The basic principle of operation is that the central heat source generates a pulse of heat energy. This pulse diffuses radially from the center of the probe by heat conduction and is advected by the ambient ground water. The direction and relative magnitude of the advective ground-water velocity can be determined by measuring the temperature difference between opposite pairs of thermistors (see Figure 5.1). Various factors affect the performance of the instrument, including thermal conductance of the solid and liquid phases, surface area of the solid phase, thermal transfer coefficient of the liquid phase and the advective transport rate of the fluid phase (Kerfoot, 1982).

The flow meter is 4.4 cm in diameter and can be used with a simple end cap packed with glass beads in a 5-cm well. The glass beads are packed around the thermistors and heat source in order to eliminate heat convection and to insure a continuous porous medium from the aquifer into the borehole for more accurate velocity measurements. A diagram of the 5 cm end cap and flow meter probe is shown in Figure 5.2.

This particular model of the flow meter is designed to be used primarily with 5-cm well casing, but the manufacturer provides two different packer configurations to allow the flow meter to be used in 10-cm well casings. These two packers are shown in Figure 5.3. The first is a pneumatic packer, consisting of inflatable tubes above and below the thermistor array. A nylon mesh sock is installed between the tubes which contains the glass beads and thermistor array. This sock expands outward to grip the inner sides of the well casing when the tubes are inflated, in theory providing a continuous porous medium in the borehole, similar to the 5 cm end cap arrangement.

The second packer shown in Figure 5.3 is somewhat simpler in design than the pneumatic packer. It is referred to as the "fuzzy packer", and consists of a simple cylinder with an outside diameter equal to the inside diameter (or slightly less) of a 10-cm well casing. The fuzzy packer is filled with glass beads and the probe is screwed into it by means of an adapter. The fuzzy packer must fit into the well casing very tightly in order to achieve the continuous porous medium arrangement of the 5 cm end cap and the pneumatic packer.

In practice, the probe is lowered down the borehole to the level at which the ground-water velocity is to be measured opposite a screened or slotted section. The submerged probe creates a short duration point source of heat. After a period of time, the relative thermal differences between each of the five pairs of thermistors are displayed using a rotary switch which selects the pairs to be read. The information is then used to calculate the ground-water speed and direction.

Prior to initiation of the heat pulse, the thermistors do not necessarily show zero temperature difference between opposite pairs of thermistors even under isothermal conditions. This condition is referred to as the natural background response. The operator records the temperature differences between the five pairs of thermistors prior to inducing the heat pulse to correct for this.

The probe is provided with consistent orientation towards north by means of a set of rods that snap together in only one direction.

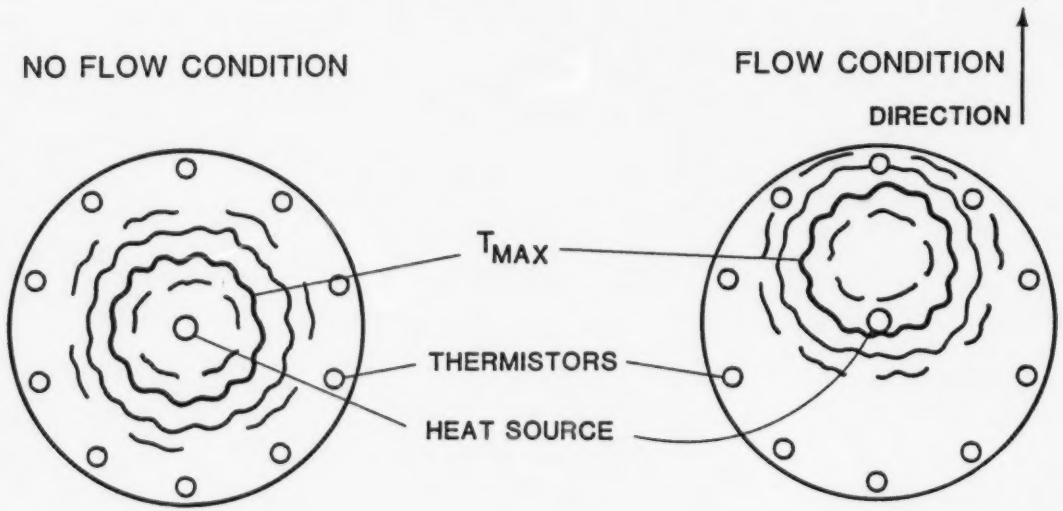


FIGURE 5.1 Operating Principle of the Borehole Thermal Flow Meter (from KV-Associates).

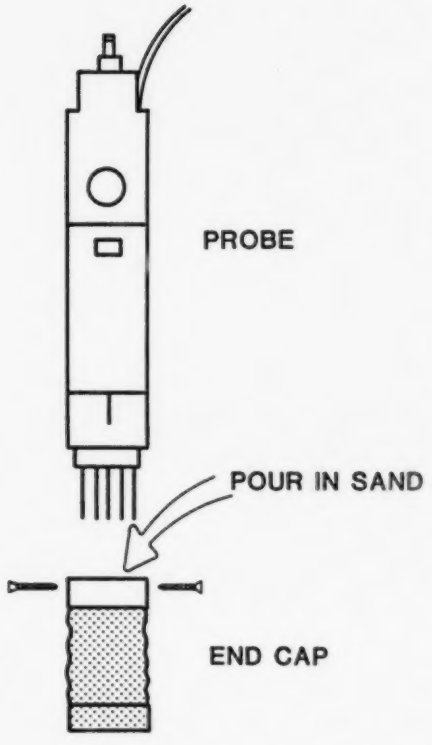


FIGURE 5.2 Diagram of the 5-cm End Cap and Probe.

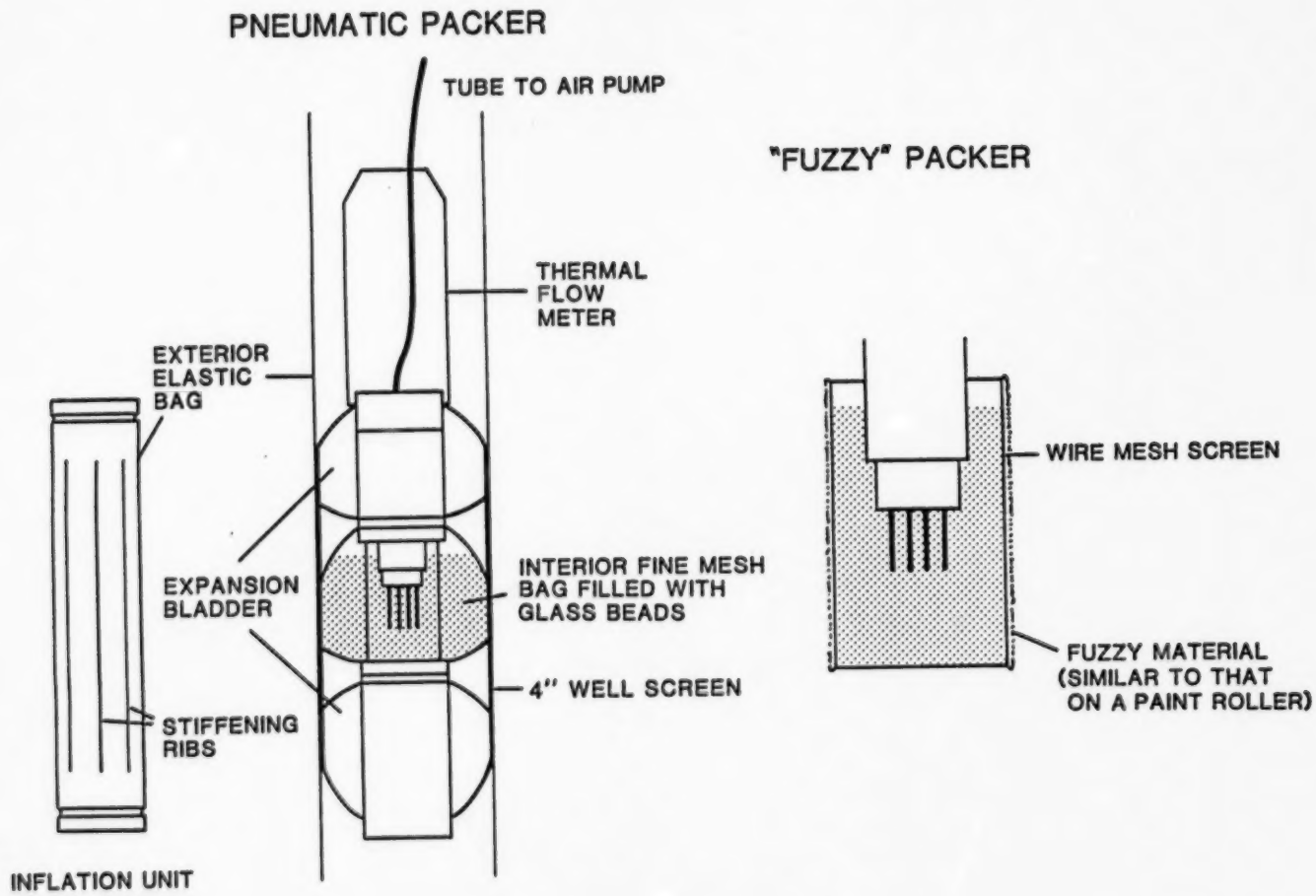


FIGURE 5.3 Diagram of the Packers for the 10-cm Borehole.

The probe is on the downhole end, and a compass is attached to the uphole snap pole. Corrections for magnetic bearing are made with a Brunton compass, and the standard practice is to orient the number 1 thermistor towards true north.

Because the probe measures the relative temperature difference between thermistor pairs at a set time after the heat pulse is emitted, the measurement of ground-water speed is a relative number which must be calibrated against some set of standards. The manufacturer provides a small calibration chamber in the shape of a 15-cm t-tube. The calibration process involves filling the horizontal portion of the t-tube (see Figure 5.4) with porous material, embedding the flow meter in the porous material, and inducing a series of known flow rates through the t-tube. The relative measurements of the t-tube are plotted against the corresponding known flow rates, thus providing a purely empirical calibration curve.

POTENTIAL PROBLEMS

There are a number of significant problems associated with the calibration technique and instrument usage. If the porosity and permeability of the porous material are the same as that of the formation to be measured in the field, then the calibration is exact. The manufacturer offers no way of correcting the velocities for different aquifers, other than conducting t-tube calibration experiments for each aquifer material. In addition, the aquifer material placed in the t-tube has been disturbed and probably has hydraulic characteristics different from the in-situ values.

Several potential problems and questions arose concerning the applicability of the thermal flow meter after initial field testing of the equipment (Hess, *et al.*, 1984). They included the following:

- Effect of the two different packers on the ground-water velocity measurements.
- Low flow velocity measurement limit.
- Suitability of the t-tube calibration chamber to construct calibration curves.

In order to solve these problems and answer the questions, a number of specific goals and objectives were developed.

GOALS AND OBJECTIVES

There are four primary goals of this study:

1. Evaluate calibration procedures for the flow meter.
2. Determine limits of accuracy and precision under controlled laboratory conditions.
3. Develop methods and techniques to extend and improve accuracy of the flow meter.
4. Develop methods to yield hydraulic conductivity information from the flow meter.

In order to achieve these goals, five specific objectives were developed:

1. Construct a sand box flow chamber for calibration experiments to allow comparison with the t-tube.
2. Conduct experiments with the t-tube calibration chamber and the sand box to determine t-tube calibration accuracy.

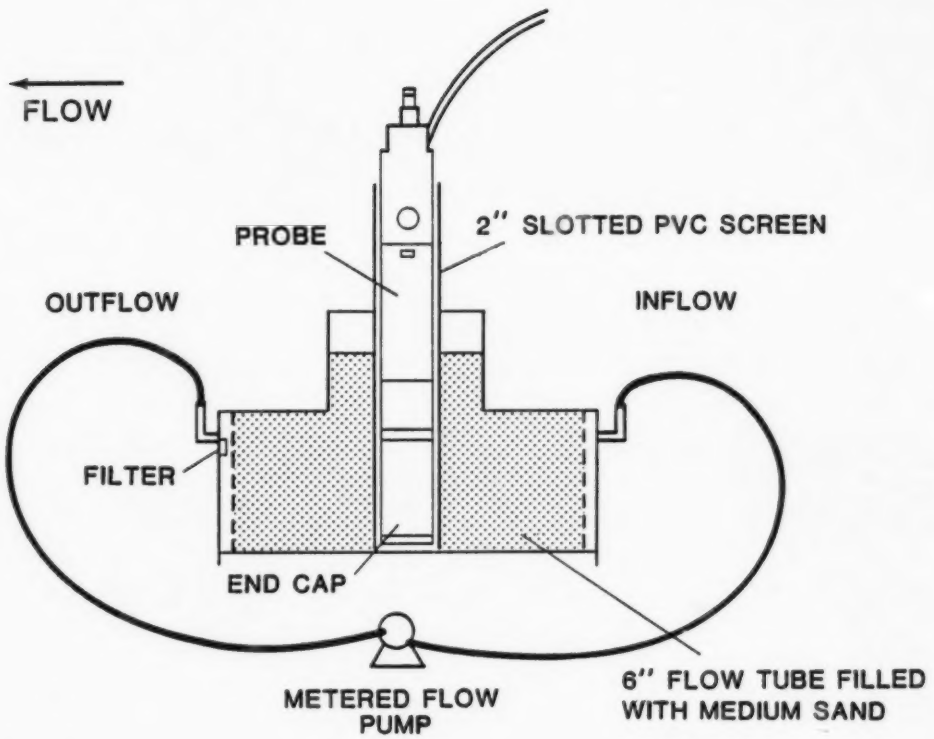


FIGURE 5.4 Diagram of the T-Tube Calibration Chamber (from KV-Associates).

3. Test the 4.4-cm end cap and the 10-cm packers in the t-tube and the sand box for accuracy and precision.
4. Develop solutions for flow around and through a cylinder (packer) of different hydraulic conductivity than the surrounding aquifer.
5. Derive equations to allow determination of hydraulic conductivity using the flow meter from the solutions developed in (4).

DESIGN AND CONSTRUCTION OF THE SAND BOX FLOW CHAMBER

The sand box was designed to allow precision control and repeatability of the groundwater velocity and to have uniform flow characteristics throughout the vertical cross-section. Numerous 5- and 10-cm well casings had to be installed, thus the dimensions of the sand box are rather large: 1.2 m by 1.2 m (cross-sectional area in direction of flow) by 2 m (length of flow path). The sand box is constructed of 3/8 inch plexiglas, and is held together with angle iron and braced with 2x4 and 2x6 beams. Figure 5.5 is set of engineering drawings, providing the construction details of the sand box. The end chambers provided constant head reservoirs which could be adjusted in height with a precision of 0.01 cm, providing excellent reproducibility of flow rates through the sand box. Figure 5.6 is a diagram of the well casing arrangement within the sand box. Each well casing was placed at least three casing diameters away from its nearest neighbor. Some of the well casings were deliberately placed near a wall to allow study of edge/wall effects.

Uniform size silica sand of #16 sieve size was used in the sand box (geometric mean size 1.19 mm). This sand size was chosen primarily to prevent sand grains from entering the casing slots. When the sand was emplaced in the box, care was taken to avoid stratification. Using Darcy's Law, the hydraulic conductivity of the sand was calculated to be 252 m/day.

Determining the porosity is of primary importance. The volumetric flow rate (Q), cross-sectional area (A), effective porosity (n) and pore velocity (v) are related by the following simple equation:

$$v = \frac{Q}{A\ n}$$

In this equation, Q and A can be measured with great accuracy. It is important to have a value for the effective porosity that is equally accurate, so that the velocity can be calculated accurately from the flow rate. A number of different methods were tried to calculate porosity, with calculated values ranging from approximately 35-45%. Rather than take an average, it was decided that the most accurate and appropriate method was a conductive tracer test in which breakthrough curves were constructed. The effective porosity was then calculated based on time-distance relationships for peak arrival from one well to another. The value calculated from this procedure was 43.7%. Table 5.1 is a summary of the relevant physical and hydraulic parameters of the sand box.

SUMMARY OF EXPERIMENTS

The experiments are divided into four categories which are summarized in this section. Table 5.2 summarizes the experiments that are discussed in this section, and their relevant parameters.

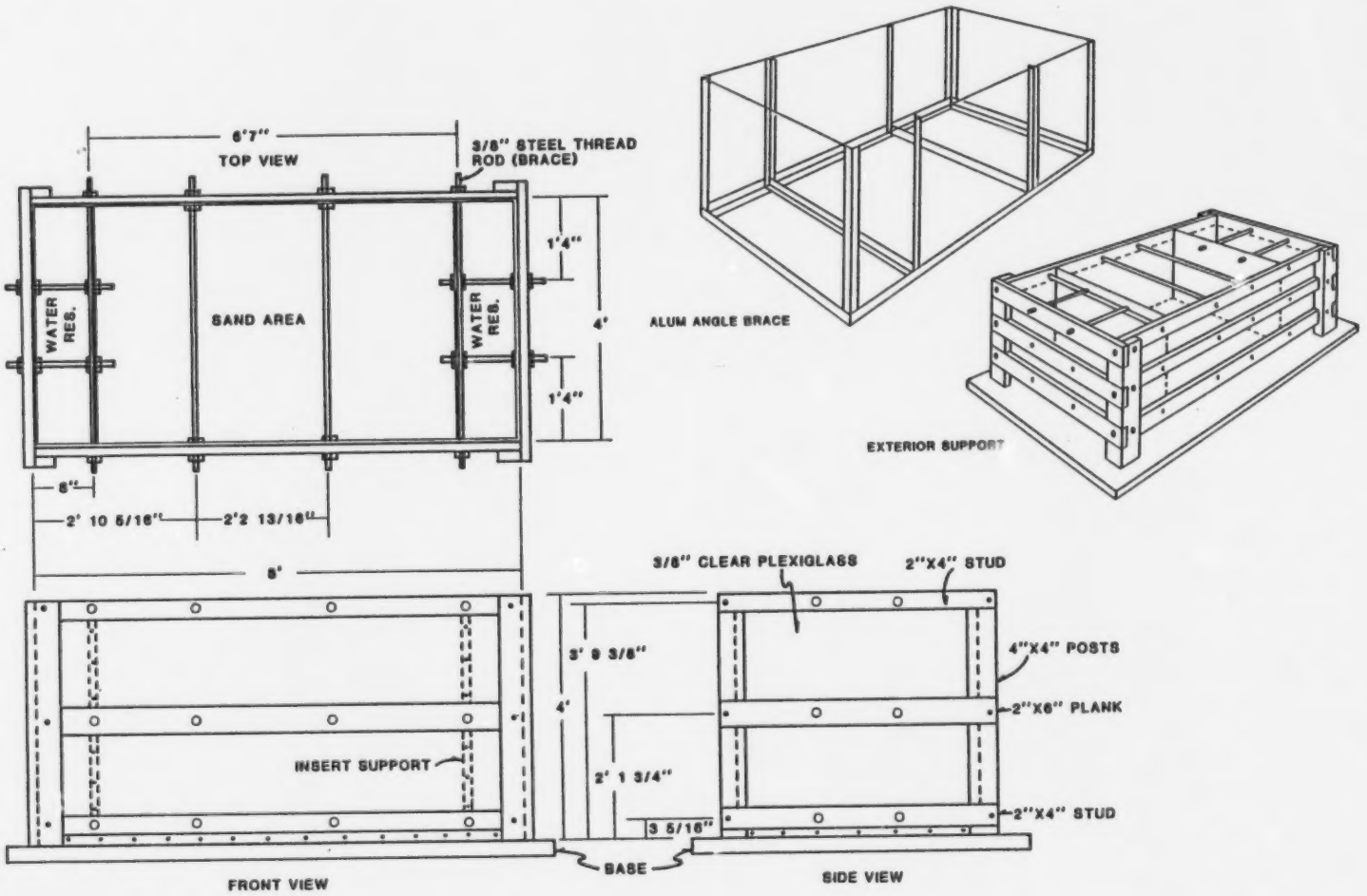


FIGURE 5.5 Construction Details of the Sand Box.

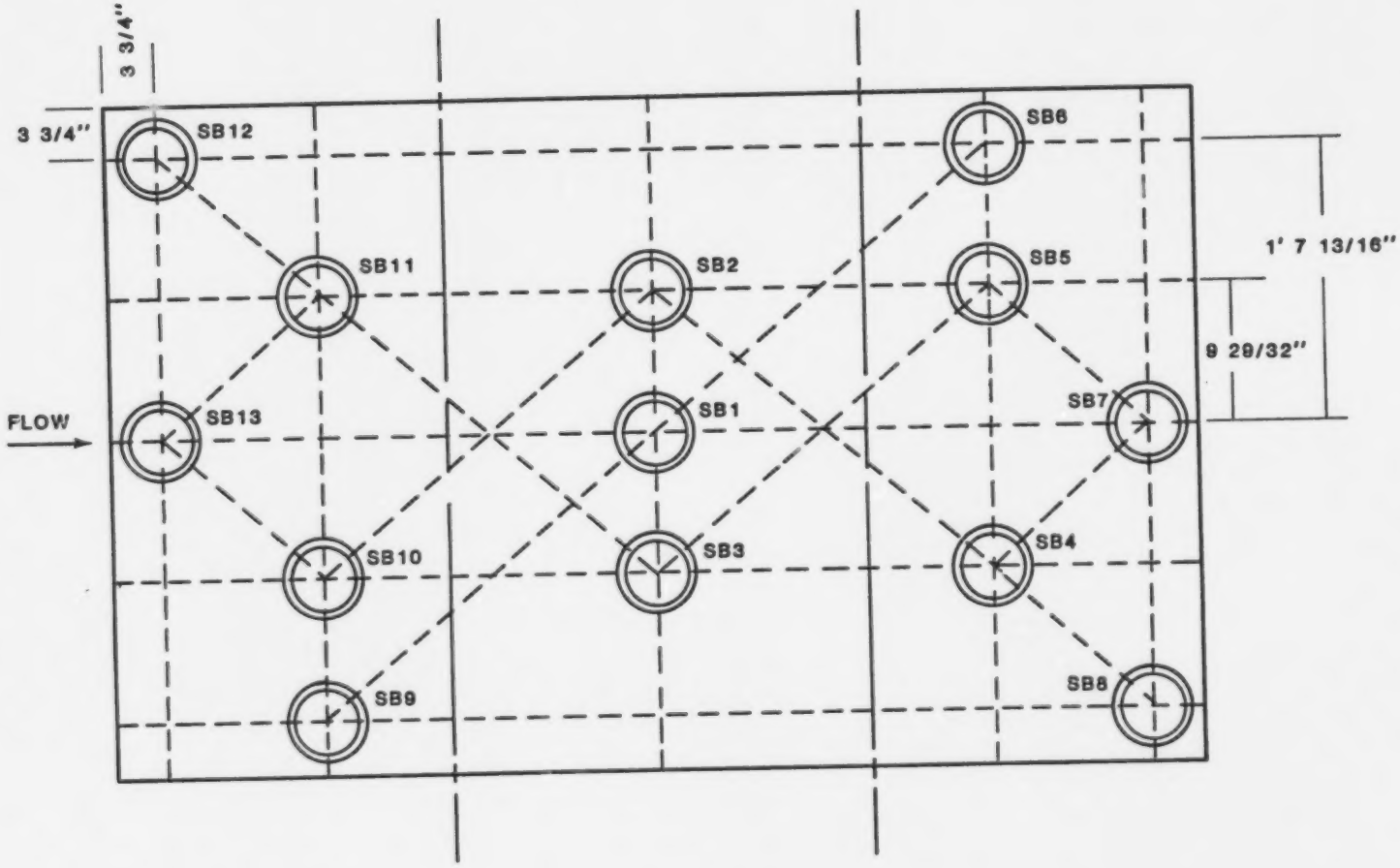


FIGURE 5.6 Placement of the Well Casings in the Sand Box.

Table 5.1	
Physical and Hydraulic Parameters of the Sand Box	
PARAMETER	VALUE
average grain size	1.19 mm
hydraulic conductivity	252 m/day
effective porosity	43.7%

The initial evaluation experiments included work with the instrument in open water, and with the instrument inserted in sand without the end cap (naked probe in sand). Experiments were also conducted to determine basic characteristics of the instrument, including bias and other parameters. This work helped gain familiarity with the instrument, but the results were relatively insignificant and are not reported here.

A 5-cm well casing was placed inside the t-tube. With the flow meter inside the casing, experiments were conducted for a range of velocity measurements. This set of experiments was repeated in the sand box, providing a direct comparison of the calibration in the t-tube and in the sand box for the 5-cm casing and end cap.

The third set of experiments was conducted similar to the second set, except that the pneumatic packer was used with 10-cm well casings in both the t-tube and the sand box.

Similarly, the fourth set tested the fuzzy packer calibration in the t-tube and the sand box. The fuzzy packer experiments were performed using the same 10-cm well casings that were used for the pneumatic packer.

EXPERIMENTAL RESULTS

The type of packer chosen to be used with the instrument had by far the strongest effect on instrument accuracy and operational limitations. Therefore, discussion of experimental results will be grouped into three categories on the basis of the packer tested. The first category will include all experiments with the 5-cm end cap (i.e. all experiments conducted with the 5-cm well casing). The second category will include all experiments with the pneumatic packer and the third category will be all fuzzy packer experiments.

Experiments using the 5-cm end cap in 5-cm well casing

This set of experiments follows the calibration procedure for the 5-cm end cap as recommended by the manufacturer. The data from experiments 201-A3.1-4 are plotted in Figure 5.7. The y-axis is the velocity* in the t-tube. The x-axis is the vector sum of the temperature

*Actually, the flow rate is the measured parameter, and the velocity is calculated by knowing the porosity.

Table 5.2

Summary of Experiments

Experiment Number	Place	Casing Size (cm)	Packer Type	Velocity (m/day)
201-A3.1	t-tube	5	end cap	5.98
201-A3.2	t-tube	5	end cap	3.93
201-A3.3	t-tube	5	end cap	2.07
201-A3.4	t-tube	5	end cap	0.87
201-B3.1	sand box	5	end cap	5.26
201-B3.2	sand box	5	end cap	3.74
201-B3.3	sand box	5	end cap	2.23
201-B3.4	sand box	5	end cap	1.02
201-B3.5	sand box	5	end cap	0.55
201-B3.6	sand box	5	end cap	0.35
201-B3.7	sand box	5	end cap	0.195
201-B3.8	sand box	5	end cap	0.080
401-A2.1	t-tube	10	pneumatic	5.66
401-A2.2	t-tube	10	pneumatic	3.83
401-A2.3	t-tube	10	pneumatic	1.90
401-A2.4	t-tube	10	pneumatic	0.89
401-B2.1	sand box	10	pneumatic	5.26
401-B2.2	sand box	10	pneumatic	4.39
401-B2.3	sand box	10	pneumatic	2.22
401-B2.4	sand box	10	pneumatic	1.03
401-B2.5	sand box	10	pneumatic	0.55
401-B2.6	sand box	10	pneumatic	0.35
401-B2.7	sand box	10	pneumatic	0.20
401-B2.8	sand box	10	pneumatic	0.10
401-A3.1	t-tube	10	fuzzy	5.48
401-A3.2	t-tube	10	fuzzy	3.99
401-A3.3	t-tube	10	fuzzy	2.10
401-A3.4	t-tube	10	fuzzy	1.05
401-B3.1	sand box	10	fuzzy	5.21
401-B3.2	sand box	10	fuzzy	3.74
401-B3.3	sand box	10	fuzzy	2.24
401-B3.4	sand box	10	fuzzy	1.04
401-B3.5	sand box	10	fuzzy	0.55
401-B3.6	sand box	10	fuzzy	0.35
401-B3.7	sand box	10	fuzzy	0.22
401-B3.8	sand box	10	fuzzy	0.10

difference between the five opposing thermistor pairs. The plotted temperature difference was calculated according to instructions provided by the manufacturer. The arrows placed above the data points are the indicated directions for each experiment. North (or "up") is arbitrarily chosen as the true direction of flow. Hence, an arrow pointing north represents a measurement with essentially no error in directional indication.

The data show an excellent linear relationship between the temperature difference and the true velocity of the fluid. The flow meter can read up to approximately 500 relative temperature units, so the response covers about 20% of the instrument range.

Figure 5.8 shows the results from the series of experiments using the 5-cm end cap in the sand box. A good calibration is shown for the data in the velocity range from about 0.5 m/day to the maximum velocity tested (about 5 m/day). However, the directional error gets large for velocities less than 1 m/day. The two diverging arrows near the bottom of the graph indicate the range of directions measured by repeating the experiment at that particular velocity.

The velocity magnitude error gets large below 0.5 m/day. This error at low velocities is attributed to the fact that the water is moving very slowly through the end cap and the diffusion of the heat pulse dominates the advective transport. Note that the average directional measurement is still towards north, indicating that repetitive measurements in the field may provide a direction of acceptable accuracy. The resulting temperature difference is too small for the thermistor pairs to measure. This will be discussed further in the following sections on the other two packers.

The sand box calibration curve for the 5-cm end cap (Figure 5.8) is somewhat non-linear, compared to the linear calibration in the t-tube (Figure 5.7). One reason suggested for the non-linear calibration curve in the sand box was related to the method used to control flow rate in the sand box. The flow rate (and therefore velocity) was set by establishing constant heads at different levels in the two end chamber reservoirs. Inaccuracies in setting the constant heads could have caused a non-linear relationship between head differences and flow rates. This hypothesis was eliminated by plotting Figure 5.8 as flow rate (which is directly measured) versus flow meter units for the experiment series. The same non-linear curve was observed.

Another possible reason for the non-linearity is that the sand-box may not be operating with truly one-dimensional flow. On the basis of some simple dye tracer tests, the observed flow paths appear to be essentially horizontal. Therefore, it is not known why the non-linearity was observed in this set of experiments at this time. Because the same porous medium was used for the t-tube and the sand box, a much better agreement was expected for the two calibration curves.

Experiments using the pneumatic packer

A 10-cm well was installed in the t-tube for the pneumatic packer and fuzzy packer experiments. The data for the pneumatic packer experiments are shown in Figure 5.9. The results are much different than those for the 5-cm end cap. The total instrument response was about 5 flow meter units, or only about 2% of the instrument range. As seen in Figure 5.9, a very small change in thermistor temperature difference indicates a large change in actual velocity. The arrows show that the directional accuracy is even worse than the magnitude

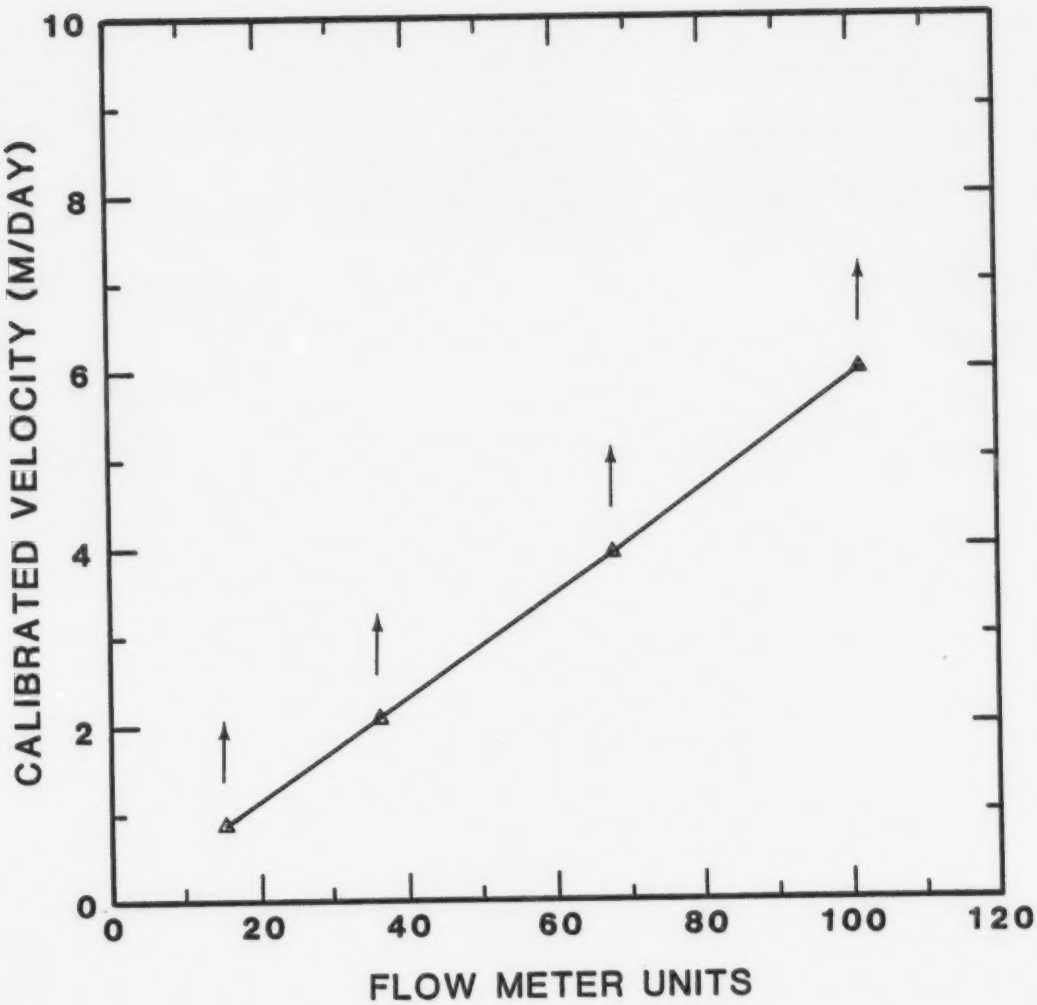


FIGURE 5.7 T-Tube Calibration of the 5-cm End Cap.

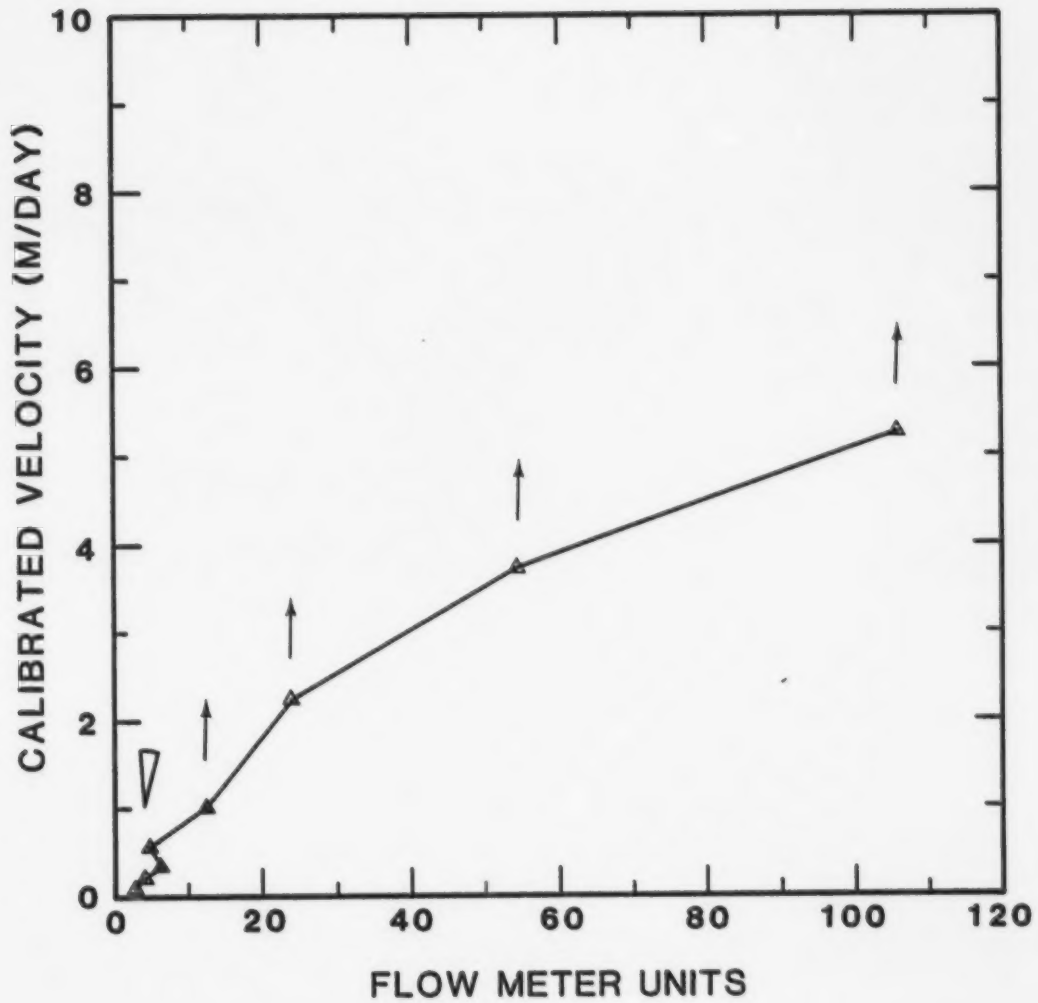


FIGURE 5.8 Sand Box Calibration of the 5-cm End Cap.

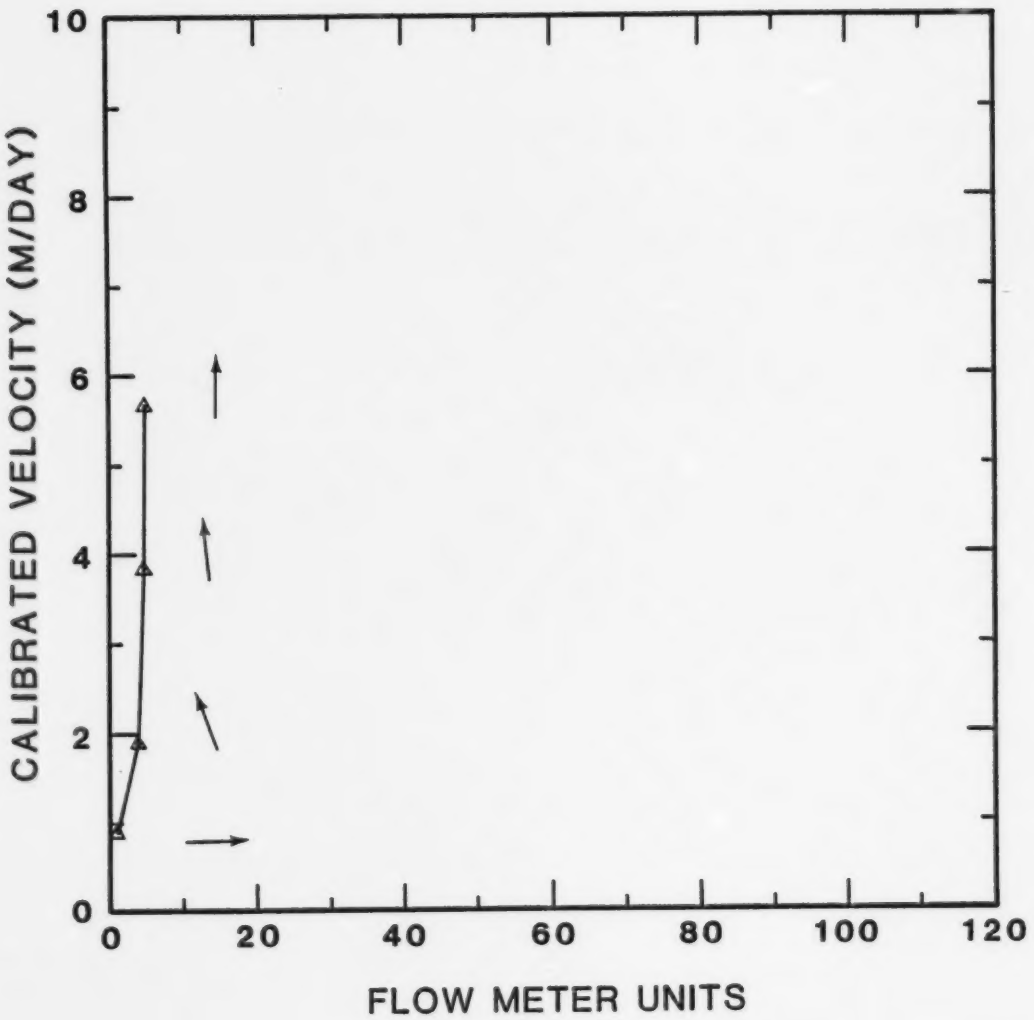


FIGURE 5.9 T-Tube Calibration of the Pneumatic Packer.

accuracy, and is useless at velocities less than 3 m/day.

Figure 5.10 shows the analogous experiments in the sand box (i.e. same parameters as in the t-tube). The instrument response is about 50 flow meter units, as opposed to only 5 in the t-tube. A larger response indicates larger temperature differences and therefore more advective transport across the thermistors. Since the t-tube and sand box velocities are in the same range (roughly 0.5 to 5 m/day), it can be concluded that the velocity in the packer is higher when it is in the sand box than when it is in the t-tube. The explanation for this is that the ratio of slotted area to total flow area is smaller in the t-tube than in the sand box. It can be concluded that the t-tube does not provide an acceptable calibration procedure for the pneumatic packer because of the edge and wall effects of the t-tube.

The directional accuracy in the sand box for the pneumatic packer is fairly good from 1 m/day through the highest velocity measured (about 6 m/day). However, for the experiments with velocities above 1 m/day, there is an average bias of +7 degrees (with a standard deviation of +/- 3 degrees). Several of the experiments were repeated several times without moving the probe, and the measured direction was the same to within 0.5 degree. It is therefore believed that this bias or offset is caused by the pneumatic packer rather than experimental error.

The fan-shaped symbol near the bottom of Figure 5.10 shows the range of indicated direction for the velocities less than 1 m/day. The large variation in velocity magnitude and direction is attributed to the fact that in this velocity range, the amount of water moving through the packer is very small. At low velocities, the advective transport is dominated by the diffusive heat transport. As a result, the heat pulse is spreading primarily by diffusion, and the pulse reaches all thermistors at almost exactly the same time. When the vector addition is performed, the vectors are primarily noise and the resulting magnitude and direction are essentially meaningless.

Experiments using the fuzzy packer

The calibration curves for the fuzzy packer in the t-tube and the sand box are shown in Figures 5.11 and 5.12 respectively. With the fuzzy packer in the t-tube, the flow meter produces a marginally useful calibration curve, although the directions become unreliable below about 3 m/day. In Figure 5.12, the data show that the flow meter cannot be calibrated with the fuzzy packer in the sand box; there is just no correlation established between the flow meter units and the actual velocity.

At first, it seems odd that the pneumatic packer calibrates better in the sand box than in the t-tube, while the reverse is true for the fuzzy packer. The reason is that the fuzzy packer fits into the 10 cm well casing very loosely, leaving a 0.5 cm annulus between the packer and the inside of the casing wall. The result is that water entering the casing preferentially flows through the annulus rather than through the packer. The wall effects of the t-tube cause a slightly better calibration than is possible in the sand box. The sand box approximates the conditions in an actual aquifer more closely than the t-tube, so the conclusion is that the fuzzy packer is not recommended for use in actual ground-water investigations.

Instrument accuracy and repeatability

Using the 5-cm end cap and flow meter in the sand box, several experiments were repeated to get information on the accuracy and repeatability of the flow meter. The

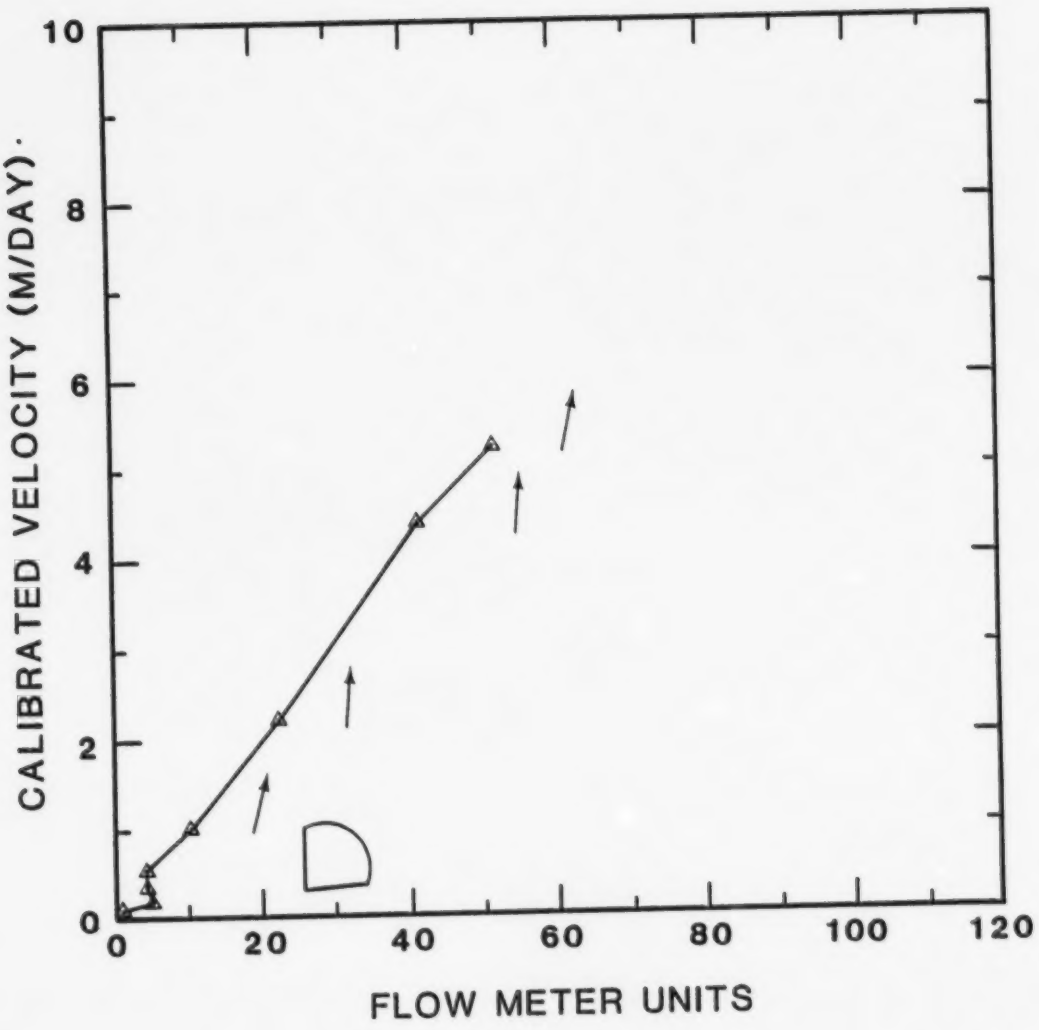


FIGURE 5.10 Sand Box Calibration of the Pneumatic Packer.

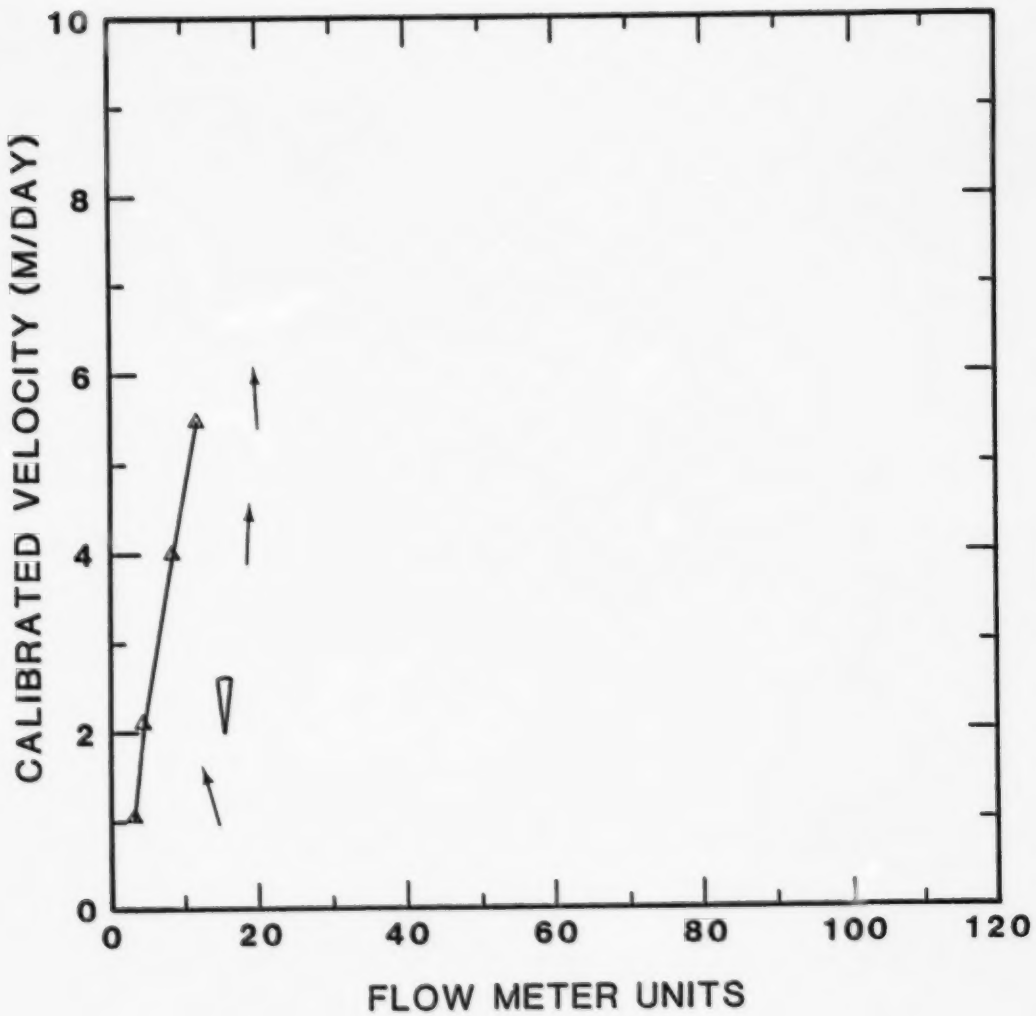


FIGURE 5.11 T-Tube Calibration of the Fuzzy Packer.

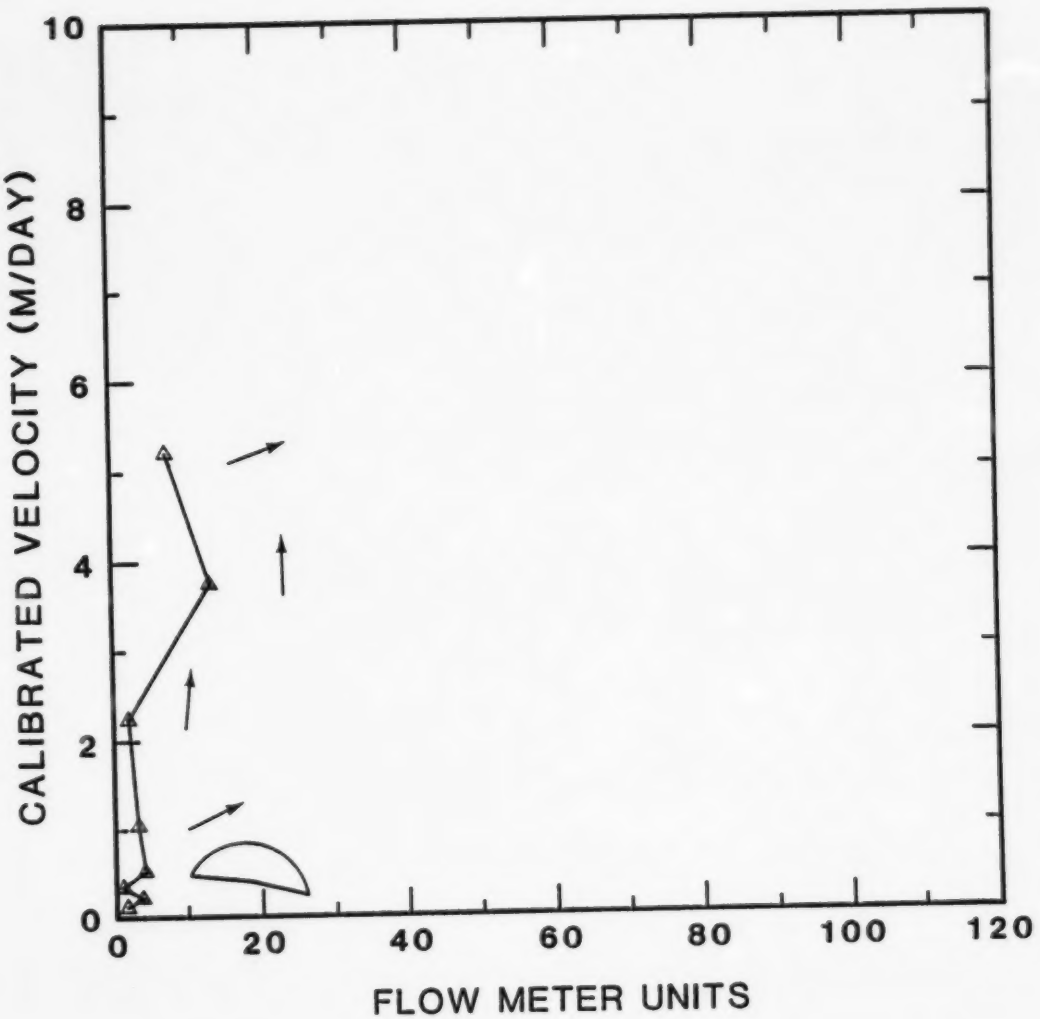


FIGURE 5.12 Sand Box Calibration of the Fuzzy Packer.

following results are valid for 5-cm end cap packer only, and for velocities greater than 0.5 m/day. Several measurements were taken successively without moving the probe or changing flow conditions. The standard deviations were all less than 2% of the averages. If the probe was removed and replaced to its original orientation and vertical position (to the best of the operator's ability to do this manually), and under the same flow conditions, the standard deviations were still less than 2%. The averages of the temperature differences (i.e. velocity magnitudes) were about the same also. However, the averages of the indicated velocity directions were usually different by about 5 degrees. The differences varied, and seemed to indicate that it is not possible to reliably place the instrument in the borehole with better than 5 degrees of directional accuracy. For real life problems, this kind of accuracy is more than adequate considering the normal uncertainty and spatial variability in aquifer hydraulic parameters.

THEORETICAL DEVELOPMENT

Introduction

The calibration techniques provided by the manufacturer are purely empirical, relating measured velocity to instrument readout. In the previous section, we have shown that the calibration technique suffers from numerous problems. Even for the 5-cm end cap in a 5-cm well, the calibration curves for the sand box are different than for the t-tube, although exactly the same type of sand was used for both sets of experiments. Bringing disturbed aquifer material in from the field and using it in the t-tube to develop a site-specific calibration curve would be very questionable based on the comparison experiments done in this study.

On the basis of the poor calibration comparisons in the laboratory experiments, it would be very desirable to develop a way to directly measure velocity magnitude. The theoretical work in this section addresses this goal. In addition, it goes a major step further and outlines a technique to calculate formation hydraulic conductivity from the measurements taken by the flow meter. This technique represents a potentially very important application of the flow meter that has not previously been considered.

Direct calculation of aquifer fluid velocity

From a theoretical standpoint, the problem can be thought of as flow around and through a cylinder of hydraulic conductivity different from the surrounding aquifer. The flow meter with the 5-cm end cap in a 5-cm well can be thought of as the permeable cylinder. It is assumed that flow through the end cap packed with glass beads obeys Darcy's Law and is steady-state. Another assumption is that the hydraulic losses in the casing slots are negligible. This is a good assumption under natural flow conditions, which are normally well below the transition from laminar to turbulent flow.

The solution is obtained through application of complex potential theory. Boundary conditions are applied at the cylinder (packer) boundary. The boundary conditions state that flow must be the same in the aquifer and the packer as the boundary is approached. The potential must also be the same as the boundary is approached. The complete derivation is quite lengthy and can be found in Wheatcraft and Winterberg (1985). The solution is in the form of two complex potentials, one for the aquifer (w_a), and one for the packer (w_p):

$$w_a = U\ z + \frac{U\ K'\ \ a^2}{z} \tag{5.1}$$

and

$$w_p = U\ K''\ z\ , \tag{5.2}$$

where

$$U = \frac{q_o}{K_a}\ ,$$

$$K' = \frac{1-K_r}{1+K_r}$$

$$K'' = 2\ \frac{K_r}{1+K_r}$$

$$K_r = \frac{K_p}{K_a}\ ,$$

$z = x + i\ y$, (complex variable).

q_o = specific discharge = $V_a\ n_a$

V_a = aquifer pore velocity,

n_a = aquifer porosity,

K_a = hydraulic conductivity of the aquifer,

K_p = hydraulic conductivity of the packer.

These complex potential equations can be separated into real and imaginary parts. The real part is related to the potential and the imaginary part is related to the stream function. Figure 5.13 shows the streamlines in the vicinity of the packed borehole for several values of K_r. For a packed borehole that is more permeable than the aquifer, fluid preferentially moves into the packer, causing greater velocity in the packer than in the aquifer. When the packed borehole is less permeable than the aquifer, fluid tends to move around the borehole, causing the packer velocity to be less than the fluid velocity in the borehole.

To obtain the pore velocity in the packed borehole, the stream function equation is written on the borehole boundary. Equations (5.1) and (5.2) are both valid on the borehole boundary. Equation (5.2) will be used because it is algebraically simpler. The amount of flow through the borehole packer can be determined by finding the particular streamline which is tangent to the borehole. The value of the tangent streamline, Ψ_t represents the flow that moves through half of the borehole (the half that is on the positive side of the x-axis), as seen in Figure 5.14. Therefore, the total flow through the cylinder, Q_p, is twice the value of Ψ_t.

On the cylinder boundary, the stream function can be written by obtaining the imaginary part of equation (5.2):

$$\Psi = K_1 \, \mathrm{Im}(w_p) = K'' \;\; q_o \;\; y \;\; . \tag{5.3}$$

The tangent streamline, Ψ_t, occurs at the point $x = 0$, $y = r_p$, and its value is (see Figure 5.13):

$$\Psi_t \; = K'' \;\; q_o \;\; r_p \;\; . \tag{5.4}$$

The total flow through the borehole packer, Q_p, is:

$$Q_p \; = 2\Psi_t \; = 2 \; r_p \;\; K'' \;\; q_o \;\; . \tag{5.5}$$

But Q_p can also be expressed as velocity in the borehole times borehole diameter:

$$Q_p \; = V_p \;\; (2r_p) \; n_p \;\; . \tag{5.6}$$

By equating the two expressions for Q_p (eqs. 5.5 and 5.6):

$$q_o \; = \frac{V_p \;\; n_p}{K''}$$

Substituting in the expression for K'' :

$$q_o \; = \frac{V_p \;\; n_p \;\; (1+K_r)}{2K_r} \;\; . \tag{5.7}$$

Equation 5.7 is an extremely important development. If all of the variables on the right hand side are known, one can directly calculate the average specific discharge for the aquifer. In theory, equation 5.7 eliminates the need for empirical calibration of the flow meter with the t-tube. Based on the questionable results of the calibration experiments, this would be a very desirable thing to be able to do.

Equation 5.7 requires the instrument to actually measure the borehole packer velocity, (V_p). However, the thermal flow meter reads out in "flow meter units," which are actually temperature differences between thermistor pairs. The flow meter needs to be modified to allow calculation of the packer velocity directly. Such a modification would require that the

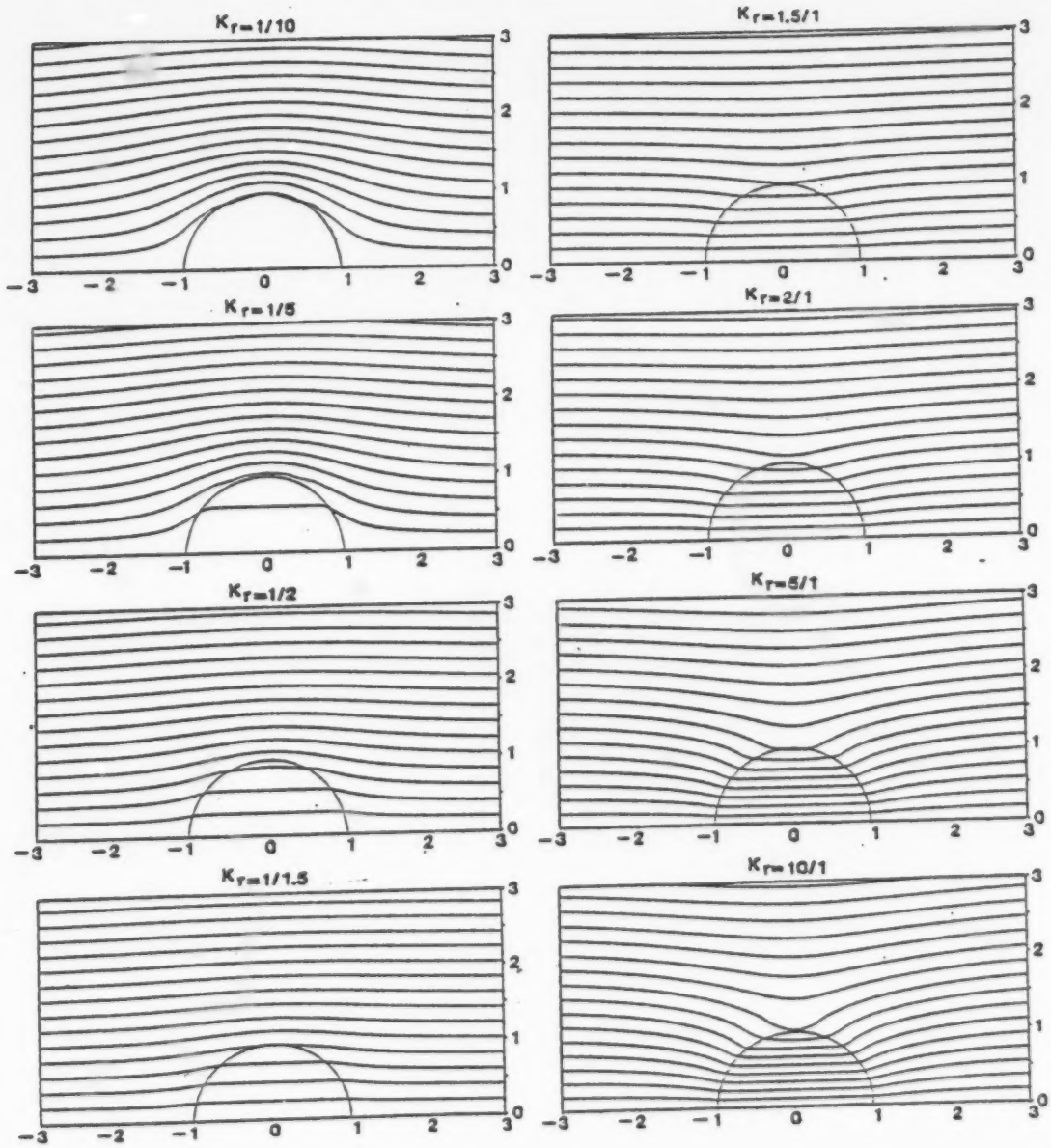
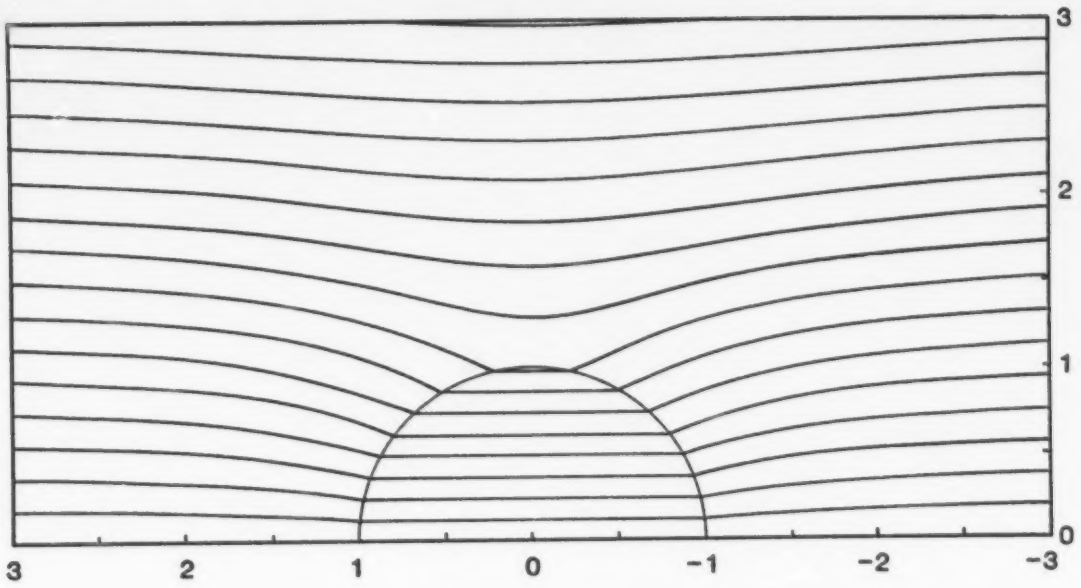
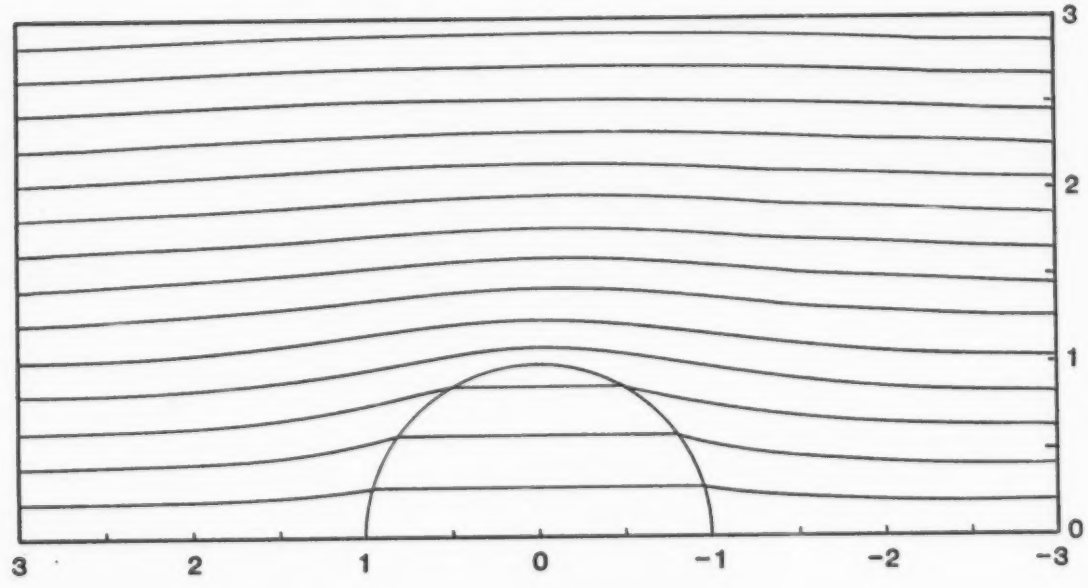


FIGURE 5.13 Streamlines Moving Around and Through a Borehole Packer for Different Hydraulic Conductivity Ratios.



k1=1 k2=5

UNIFORM FLOW FIELD



k1=2 k2=1

FIGURE 5.14 Tangent Streamline for Determination of Aquifer Fluid Velocity and Hydraulic Conductivity.

output from each thermistor be recorded on a chart recorder as a function of time (starting when the temperature pulse is initiated). Using the peak arrival times of the heat pulse for each thermistor, the advective portion of the heat transport could be obtained. This in turn would allow direct calculation of the fluid velocity in the packer.

The other parameters on the right hand side of equation 5.7 are easier to obtain in some cases. The packer porosity and hydraulic conductivity (n_p and K_p) can be measured in the laboratory, and the aquifer hydraulic conductivity can be obtained independently from aquifer pumping tests, or other means.

It should be noted that the aquifer hydraulic conductivity (K_p) measured by a pump test may be different from the K_p immediately adjacent to the vertical position where measurement with the flow meter is being taken. In such a case, the K_r would be incorrect. This problem will be directly addressed in the following section.

Equation 5.7 has been written in terms of q_s, but if the aquifer velocity varies vertically only as a function of porosity, (e.g. due to variations in litholgogic stratification) then the gamma density log will allow conversion of the specific discharge into aquifer fluid velocity in situations where the relationship between effective and total porosity is known.

Determination of hydraulic conductivity using the thermal flow meter

If the aquifer hydraulic conductivity is unknown, equation 5.7 can be used to determine it. The process consists of conducting two experiments with the flow meter, using two different packers that have different, but known hydraulic conductivities, K_{p1} and K_{p2}. Thus we have two equations, and two unknowns. In the first experiment, we use a packer with hydraulic conductivity K_{p1}, obtaining a packer velocity V_{p1}:

$$q_s = \frac{V_{p1}\, n_{p1}\, (1+K_{p1}/K_a)}{2\, K_{p1}/K_a)} \,. \tag{5.8}$$

In the second experiment, we change the packer so that we have K_{p2} and V_{p2}:

$$q_s = \frac{V_{p2}\, n_{p2}\, (1+K_{p2}/K_a)}{2\, (K_{p2}/K_a)} \,. \tag{5.9}$$

The porosities, n_{p1} and n_{p2}, may be different, but they can be determined in the laboratory along with the hydraulic conductivities, K_{p1} and K_{p2}.

The two unknowns are q_s and K_a. Thus by conducting two experiments, we can actually determine the aquifer hydraulic conductivity as well as the specific discharge. This is a very significant finding, because until this theoretical development, there has been no reason to suspect that the thermal flow meter could be used to obtain the aquifer hydraulic conductivity.

Equations (5.8) and (5.9) can easily be solved for the two unknowns K_a and q_o:

$$K_a = K_{p2}\left(\frac{q_{pr}-1}{K_{pr}-q_{pr}}\right), \tag{5.10}$$

and

$$q_o = \frac{q_{p2}}{2}\left(\frac{K_{pr}-1}{K_{pr}-q_{pr}}\right), \tag{5.11}$$

where $q_{pr} = \dfrac{q_{p2}}{q_{p1}} = \dfrac{V_{p2}\, n_{p2}}{V_{p1}\, n_{p1}}$,

and $K_{pr} = \dfrac{K_{p2}}{K_{p1}}$.

This "two-K_p method" theoretically offers an alternative to laboratory calibration with the t-tube, which has been shown to be of questionable value. This method would require a fairly involved field procedure, and may be cumbersome for multiple measurements, but considering the problems of direct calibration, it may be the only way to obtain any data from the flow meter other than directional data.

Potential problems and limitations

It should be strongly emphasized that the method outlined in this section, while theoretically correct, has not been tested in the laboratory or in the field. Plans for future research include using the sand box laboratory constructed for this project to evaluate this method for obtaining aquifer fluid velocity and hydraulic conductivity using the thermal flow meter.

Some of the problems that may be encountered include:

1. The packer hydraulic conductivity may be subject to considerable variability from one measurement to the next, due to rearrangement of the glass beads in the packer. Sensitivity of K_p to such rearrangement is an important area of further research.
2. The accuracy of the method may be sensitive to the choice of packer hydraulic conductivities, and/or sensitive to the aquifer hydraulic conductivity relative to the choice of packer hydraulic conductivity.

These and other problems that could develop may limit the use of the method with the thermal flow meter as it is currently designed. Understanding the problems and limitations may lead to ideas for a better design of the thermal flow meter, taking into consideration the design criteria that would make the method work in practice, as well as in theory.

SUMMARY AND CONCLUSIONS

Experimental work: velocity magnitude calibration

The results of the calibration comparisons show that there are significant wall or geometric effects when using the t-tube to provide an empirical calibration curve for the thermal flow meter when used with the 5-cm end cap in a 5-cm well casing. The calibration curve was linear in the t-tube and non-linear in the sand box. Thus calibrations done in the t-tube do not apply to actual field situations. The t-tube calibration is even more questionable when considering the fact that the t-tube must be filled with disturbed aquifer material, which may have different hydraulic properties than the original aquifer.

The pneumatic packer had a reasonably good calibration in the sand box, but not in the t-tube. Again, the discrepancy appears to be due to the wall effects in the t-tube. The difference in the calibration curves between the t-tube and the sand box indicate that the pneumatic packer should not be used for velocity-magnitude determinations in the field.

The fuzzy packer has a linear calibration in the t-tube, but very small changes in temperature difference are indicative of large changes in velocity. This condition makes the calibration curve too sensitive to provide good correlation between temperature difference and velocity magnitude. In the sand box, there is almost no correlation between temperature and velocity, indicating that most of the fluid is moving around the fuzzy packer. The fuzzy packer is the least useful of the three packer configurations tested.

Experimental results: directional accuracy

The directional accuracy is good for velocities down to about 0.5 m/day for the 5-cm end cap. For repeated experiments in which the flow meter is not moved, accuracy is at least $\pm$ 0.5 degrees. If the flow meter is moved, the repeatability is about $\pm$ 3 degrees.

The directional accuracy for the pneumatic packer was not quite as good in the sand box as the 5-cm end cap. The pneumatic packer showed a consistent bias offset of 7 degrees to the east. The results show that the pneumatic packer can be used to determine direction for velocitites down to 0.5 m/day, even though it is not capable of being calibrated for velocity magnitude. Correction for the bias can be done by subtracting 7 degrees from the indicated direction.

The fuzzy packer is inaccurate for the direction as well as the velocity magnitude, so it should not be used at all.

In summary, the flow meter as presently marketed is only reliable for directional measurements using the 5-cm end cap and with additional caution, the pneumatic packer.

Theoretical work

Equations have been developed that express aquifer fluid velocity as a function of the fluid velocity in the borehole packer, hydraulic conductivity and porosity of the borehole packer and the hydraulic conductivity of the aquifer. With some modification to the thermal flow meter, it is theoretically possible to measure these parameters.

Therefore, the aquifer fluid velocity can be directly calculated, thus eliminating the need for the questionable t-tube calibration procedure. Although these equations are theoretically correct, they are untested. Considerable experimental work will be necessary to determine how well they work with the thermal flow meter.

The most significant result of the theoretical work is that the hydraulic conductivity of the aquifer can be calculated with the thermal flow meter. This method requires two measurements to be taken with the flow meter, with two different packers of different hydraulic conductivity. These two measurements provide two equations and two unknowns, the aquifer hydraulic conductivity and the aquifer specific discharge. If the aquifer porosity is known from other borehole logs, then the aquifer fluid velocity can be calculated as a function of aquifer depth. This "two-K_p method" theoretically provides the only known way of simultaneously obtaining aquifer hydraulic conductivity and specific discharge vector data. If it can be shown to be of practical use in the field, it will be a valuable addition to the suite of tools available to the hydrogeologist.

SECTION 6

SUMMARY AND CONCLUSIONS

INTRODUCTION

The complex nature of the ground-water contamination problem requires the collection of extensive amounts of data in order to understand the problem well enough to recommend and execute the appropriate remedial action. It is nearly impossible to collect adequate amounts of data with traditional hydrogeologic methods, thus creating a need for technology that can help answer the complex questions that arise when dealing with ground-water contamination.

Geophysical methods have been widely used in oil and mineral exploration since the 1920's. However, due to their cost and the relative simplicity of most previous ground-water problems, geophysical methods have not commonly been used for ground-water investigations. As the complexity and consequences of ground-water contamination increase, geophysics is becoming a more cost effective approach to answer the hydrologic questions associated with ground-water contamination.

Geophysical methods applicable to hazardous waste site investigations can be broken into two categories: surface and subsurface methods. Surface methods offer the advantage of relatively little capital investment at the site (no borehole is required), and rapid collection of data over a horizontal area. However, the interpretation is often ambiguous and limited in vertical resolution. Subsurface methods require a borehole and can only investigate an area immediately around the borehole. However, they provide excellent information on vertical changes in measured parameters. Also, a suite of complementary logs can potentially provide unambiguous interpretation of hydrogeologic parameters, especially in the vertical dimension.

The two approaches complement each other very well. The subsurface methods provide the necessary vertical detail for a small area and the surface methods can then extend this detail horizontally between boreholes.

This report has examined only subsurface geophysical methods. Research in surface methods is being performed by other EPA contractors. Problems of site characterization, contaminant plume detection and monitoring of contaminant plumes have been addressed using borehole geophysics.

BOREHOLE GEOPHYSICAL METHODS

Borehole methods fall into five major categories: acoustical, electromagnetic, nuclear, flow and dimension, and thermal. Major applications of these techniques include: lithologic correlation, lithology, rock density, fractures, porosity, permeability, flow, water level, water quality, temperature gradient and hole diameter.

Hardware for borehole geophysical logging consists of similar basic components for all the different tools. consisting of sensor, signal conditioners, and a recorder. The sensor or sonde receives power and transmits the signal to the surface through a conducting cable, which also serves to position the tool in the hole by means of a winch. Electronic controls at the surface regulate logging speed and direction, power to the downhole electronics, signal conditioning, and recorder responses. The return signal from the probe is a function of lithologic, fluid, and borehole parameters and is recorded and later analyzed with a computer.

LIMITATIONS OF BOREHOLE METHODS FOR HYDROGEOLOGIC HAZARDOUS WASTE INVESTIGATIONS

Borehole logging methods have been developed primarily by and for the petroleum industry. Logging tools are designed to be used in open, large diameter, deep holes. Several logging tools are usually attached to one downhole sonde that can be as much as 5 m in length. Interpretation schemes are designed to remove effects of drilling and to determine parameters that are of interest in petroleum reservoir engineering.

The typical borehole that exists at (or around) hazardous waste sites is shallow (probably less than 100 m), narrow diameter (5 cm) and cased, usually with PVC, Teflon, or some other plastic. None of the borehole tools designed for the petroleum industry are usable in such an environment. Many downhole sondes used in the petroleum industry have 4 or 5 tools attached and are 5 m long. Even if a sonde such as this could fit in a typical 30-m hole at a hazardous waste site, the bottom 15% of the hole could not be logged due to the length of the sonde. None of the open hole logging tools (such as electric logging) can be used in the PVC cased holes. Since most downhole tools are designed for high temperature, high pressure environments, they would be over-designed for the typical shallow monitoring well around hazardous waste sites. Moreover, the same tools may be subjected to hazardous chemical borehole environments in monitoring wells around hazardous waste sites for which they are not designed to withstand.

The interpretation schemes developed for the petroleum industry are designed to remove effects of drilling fluid from the data. Logging is normally done before, or just after hole completion and holes are almost never re-logged, especially after casing has been set. For hazardous waste site investigations, borehole logging will commonly be done after PVC casing has been set, and it will be desirable to re-log holes on a regular basis to monitor for changes in formation fluid chemistry and ground-water velocity.

The borehole logging parameters that are of interest to the hydrogeologist investigating ground-water contamination are quite different from the parameters commonly sought by the petroleum reservoir engineer. As a result of the above considerations, it is of primary importance to develop a new borehole logging strategy that is designed to provide the information sought by the hydrogeologist for hazardous waste site investigations.

BOREHOLE LOGGING STRATEGY FOR HYDROGEOLOGISTS

The vertical variation in hydraulic parameters within an aquifer is recognized to be of primary importance in determining the fate and transport of contaminants in ground-water systems. Traditionally, the process of hydrodynamic dispersion has been thought to be the dominant process causing contaminant mixing. Macro-scale heterogeneity and vertical stratification induce large variations in the advective flow rate of the ground water. This process has been termed macroscopic dispersion, and is the dominant mechanism controlling contaminant mixing and transport in many aquifers.

Largely because of macroscopic dispersion, traditional ground-water flow equations are inadequate to describe contaminant transport in aquifers. Although it is important to account for vertical variation in hydraulic parameters, there has been little effort to develop adequate borehole methods that would provide such parameters.

If borehole methods are to be of use for hydrogeologists, it is essential that they answer questions of hydrologic significance. In particular, the strategy outlined in this report describes how the following parameters vary with depth: porosity; hydraulic conductivity; lithology; ground-water velocity; cation exchange capacity of the formation; and electrical conductivity of the pore fluid.

Hazardous waste sites are located in every conceivable geologic setting. Each one is unique and relationships developed for one site cannot be considered valid elsewhere. It is essential that relationships used in interpretations be based on data collected at the site under study. To do this, it is necessary to drill a characterization hole at each site. The interpretation strategy combines geophysical information from the well logs and geologic information from the characterization well to answer the hydrologic questions we are interested in.

The assumption in this strategy is that the site specific relationships obtained from the calibration well hold throughout the site. Shallow, unconsolidated sediments are among the most heterogeneous deposits to be found. It is not expected that the formations will be laterally continous for the site specific relationships to hold, only that the correlations between lithologic characteristics and geophysical parameters remain the same. Even this assumption may be risky in some instances and the practicing hydrogeologist that employs this strategy must be aware of the possible variations that may exist for specific problems. Although different relationships could be developed for different formations, it is assumed that these relationships are valid throughout the formation for which they were developed. In unusual cases, it is possible that the presence of the contaminant could alter these relationships are based on fairly simple physical and chemical principles, a review of the literature along with an understanding of the mechanisms involved may make it possible to identify conditions where the contaminant might be altering the relationships used in the interpretation.

USE OF A BOREHOLE THERMAL FLOW METER FOR DETERMINATION OF GROUND-WATER VELOCITY AND HYDRAULIC CONDUCTIVITY

The traditional way of determining ground-water velocity is to calculate it using Darcy's Law, regional or local piezometric head gradient information, and effective porosity. This is an indirect measurement, and does not take into account velocity variations in the vertical dimension. A more desirable method to obtain velocity information in principle would be to

directly measure it in a borehole. One way of doing this is with a thermal ground-water flow meter, as described in Section 5.

Laboratory attempts to calibrate the instrument for velocity, including a specially designed sandbox, were not entirely successful. The data generated clearly indicated that the thermal flow meter, when used with the fuzzy packer, is inaccurate for velocity as well as direction. It is recommended that the fuzzy packer not be used at all.

Because of poor calibration comparisons in the laboratory experiments, study was initiated to develop a way to directly measure velocity magnitude. Equations were developed that express aquifer fluid velocity as a function of the fluid velocity in the borehole packer, hydraulic conductivity and porosity of the borehole packer and the hydraulic conductivity of the aquifer. With some modification to the thermal flow meter, it is theoretically possible to directly measure these parameters. Therefore, the aquifer fluid velocity can be directly calculated, thus eliminating the need for the questionable calibration procedure. Although these equations are theoretically correct, they are untested. Considerable experimental work will be necessary to determine how well they work with the thermal flow meter.

The most significant result of the theoretical work is that the hydraulic conductivity of the aquifer can be calculated with the thermal flow meter. This method requires two measurements to be taken with the flow meter, with two different packers of different hydraulic conductivity. These two measurements provide two equations and two unknowns, the aquifer hydraulic conductivity and the aquifer specific discharge. If the aquifer porosity is known from other borehole logs, then the aquifer fluid velocity can be calculated as a function of aquifer depth.

REFERENCES

Asquith, G. and C. Gibson, *Basic Well Log Analysis for Geologists,* American Association of Petroleum Geologists, Tulsa, Ok., 1982. 216 pp.

Bear, J., *Hydraulics of Groundwater,* McGraw-Hill, New York, 1979. 567 pp.

Dobrin, M. B., *Introduction to Geophysical Prospecting,* McGraw-Hill, New York, 1976. 630 pp.

Donovan, W. S. and D. W. Hilchie, *Seventh Formation Evaluation Symposium of the Canadian Well Logging Society,* Calgary, Canada, 1979.

Dresser Atlas,, *Well Logging and Interpretation Techniques; The Course for Home Study,* Dresser Industries, Inc., Houston, Texas, 1982, 350 pp.

Gal'perin, E.I., *Vertical Seismic Profiling,* Society of Exploration Geophysicists, Houston, Texas, 1974, 270pp..

Hallock, W. B., "Subterranean temperatures at Wheeling, W. Va., and Pittsburgh, Pa.," *Columbia School of Mines Quarterly,* vol. 18, pp. 148-154, 1897.

Hess, J. W., S.W. Wheatcraft, D. D. Spencer, and W. M. Adams, "Evaluation of the applicability of some existing borehole instruments to hazardous waste site characterization and monitoring," in *Proceedings of the NWWA Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations,* pp. 762-772, National Water Well Association, 1984.

Hilchie, D., *Applied Open Hole Log Interpretation,* Douglas Hilchie, Inc., Golden, Co., 1982, 220 pp..

Johnson, W.L. and W.B. Linke, "Some practical applications to improve formation evaluation of sandstone in the MacKenzie delta," in *Transactions, Fifth Formation Evaluation Symposium,* pp. R-1-R-19, Canadian Well Logging Society, Calgary, Canada, 1977.

Keller, G. V. and F. C. Frischknecht, *Electrical Methods in Geophysical Prospecting,* Pergammon Press, New York, 1966, 523 pp..

Kerfoot, W., *Groundwater Flowmeter System; Operations and Maintenance Manual; Model 30L,* K-V Associates, Inc., Falmouth, Massachusetts, 1982, 27 pp..

Keys, W. S. and L. M. MacCary, *Techniques of Water-Resources Investigations of the United States Geological Survey; Application of Borehole Geophysics to Water-Resources Investigations,* U.S. Geological Survey, Washington, D.C., 1971. 126 pp.

Mlay, M., "Coordinating protection efforts," *EPA Journal*, vol. 10, no. 6, pp. 50-60, 1984.

Pirson, S. J., *Handbook of Well Log Analysis*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1963, 326pp..

Riclo, J., "Porosity and permeability studies of some unconsolidated sediments," *Compass*, vol. 39, pp. 51-63, 1962.

Schlumberger, Ltd.,, *Log interpretation, Vol. 1-Principles; Vol. 2-Applications*, Schlumberger, Ltd., New York, 1972, 116 pp. and 112 pp..

Schlumberger, C., "Electrical logs and correlations in drill holes," *Mining and Metallurgy*, vol. 10, pp. 515-518, 1929.

Schwartz, F. W., "Macroscopic dispersion in porous media," *Water Resour. Res.*, vol. 13, no. 4, pp. 743-752, 1977.

Smith, L. and F. W. Schwartz, "A stochastic analysis of macroscopic dispersion," *Water Resour. Res.*, vol. 16, no. 2, pp. 303-313, 1980.

Ward, S. H. and D. C. Fraser, "Conduction of electricity in rocks," in *Mining Geophysics, vol. II, Theory*, pp. 197-223, Society of Exploration Geophysicists, Tulsa, Oklahoma, 1967, 300 pp..

Waxman, M. H. and L. J. M. Smits, "Electrical conductivities in oil-bearing shaly sands," *Aime Trans.*, vol. 243, pp. 107-122, 1968.

Wheatcraft, S. W. and F. Winterberg, "Steady-state flow passing through a cylinder of permeability different from the surrounding medium," *Water Resour. Res.*, vol. 21, pp. 1923-1929, 1985.

Wyllie, M.R.J., "Elastic wave properties in heterogeneous and porous media," *Geophysics*, vol. 21, pp. 41-70, 1956.